THE HYDROLOGY AND HYDROCHEMISTRY OF HIGH CREEK FEN

by

TERESA MARIE LEGG

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Dr. Peter Blanken, Department Chair

Dr. John Pitlick, Committee Member

Date:

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Legg, Teresa Marie (M.A., Geography)

The Hydrology and Hydrochemistry of High Creek Fen

Thesis directed by Associate Professor Peter Blanken

High Creek Fen is a groundwater-fed wetland located in South Park, Colorado. To date, the groundwater sources to the fen have not been identified, and the spatial and temporal variation in hydrology and hydrochemistry is not well understood. Identifying the groundwater sources to High Creek Fen is important because new housing developments in the South Park basin, which have increased groundwater withdrawals, and may threaten the hydrologic integrity of the fen. To identify groundwater sources to the fen, physical and chemical groundwater and surface water measurements were collected throughout the fen between May 25, 2007 and May 29, 2008. Results indicate that the fen is primarily fed by a shallow groundwater source originating from the northwest. A secondary source of groundwater may contribute groundwater to the eastern region of High Creek Fen. In addition, the groundwater hydrology and hydrochemistry of High Creek Fen is greatly influenced by seasonal hydrologic processes.

ACKNOWLEDGEMENTS

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CHAPTER 1: Introduction

1. Background

Watersheds throughout the United States are increasingly affected by human activities. Land use change, urbanization and global climate change present some of our greatest challenges to maintaining water quality in watersheds. Wetland ecosystems play an important role in maintaining watershed water quality, and cover approximately 6% of the Earth's surface, however they are among the most threatened hydrologic systems (Bullock and Acreman, 2003). Human activities such as draining, dredging, and filling have resulted in the loss of more than one-half of the wetland acreage in the United States, an area of approximately 110 million acres (Gibbs 2000; EPA 2001). Wetlands are especially threatened by hydrologic changes within watersheds caused by widespread groundwater withdrawals, drought and surface water diversions for agriculture. The key to maintaining watershed water quality is to understand the complex hydrology that shapes the structure and function of the hydrologic features such as wetlands (Mitsch and Gosselink 2007).

Wetlands are able to foster incredible biological diversity and high rates of primary productivity, process heavy loads of chemical inputs, and absorb floods because they are spatially and temporally heterogeneous hydrologic systems. High rates of primary occur in aerobic microenvironments within wetlands whereas other important wetland functions, such as the degradation of nutrient pollutants such as nitrate and sulfate, and the storage of organic carbon, occur in water-saturated, anaerobic microenvironments (Schlesinger 1997; Mitsch and Gosselink 1993). Microenvironments within wetlands are maintained by the hydrologic regime and thus, wetland ecosystem function is especially vulnerable to hydrologic change.

Fens, nutrient-rich wetland ecosystems, are important in promoting water quality and as carbon sinks (Chimner and Cooper, 2003; Chimner, et al., 2002). Fens cover large areas in northern temperate and polar latitudes and their distribution in North America extends from the arctic regions of northern and northwestern Canada south through the Great Lakes region and into the Midwestern United States. Fens are also present in the northeastern United States, the Appalachian Mountains and the mountainous West of the United States (Bedford and Godwin, 2003). Fens are considered long-term, net carbon sinks because plant production exceeds decomposition, and the vegetation, peat, stores large amounts of carbon (Smith, et al., 2004; Chimner, et al., 2002). However, fen carbon sequestration may be very sensitive to changes in water supply. When water table elevations decrease plant growth is often limited by lack of water. In contrast, decomposition rates often decrease in this scenario because decomposition is frequently limited by soil saturation. In water limited regions, such as the mountainous West of the United States, it is important to identify and preserve the source waters to fens.

Evidence suggests that ecosystem productivity and function of wetlands in the Rocky Mountain region of the United States are sensitive to hydrologic changes. Chimner and Cooper (2003) showed that in Rocky Mountain National Park, where surface water runoff recharges groundwater sources, surface water diversions caused groundwater table elevation declines in fens. The lower groundwater tables in the fens caused a larger aerobic surface layer to form, which promoted higher rates of heterotrophic respiration and consequently, increased carbon dioxide production. Since sub-surface saturation is an important control on heterotrophic respiration, groundwater table declines in wetland ecosystems could increase carbon dioxide emissions to the atmosphere and exacerbate global climate change. Considering the land use and environmental changes occurring in watersheds throughout the United States, it is essential to consider the impact these changes may have on wetland ecosystem function.

A number of mountain ranges within the Rocky Mountains of the western United States, including the Gros Ventre Range in northwestern Wyoming and the Mosquito Range in central Colorado, support high-elevation fen ecosystems (Cooper, 1996). The South Park basin, located on the eastern flank of the Mosquito Range, features at least 31 rich and extremely rich fens (Cooper, 1997). The South Park basin is a large intermountain valley located southwest of Denver, Colorado. The basin, approximately 3000 meters above sea level (Cooper and Sanderson, 1997), is bordered by three mountain ranges; the Front Range to the north, the Tarryall Mountains to the east, the Mosquito Range to the west. South Park is also influenced by the Elkhorn thrust fault, located on the eastern edge of the basin. The concentration of nutrient-rich fens, wetlands and springs in South Park may be due to attributed to limestone and dolomite sediments from the Mosquito Range (Johnson and Steingraeber, 2003), and extensive faulting associated with the Elkhorn thrust fault (Chapman, et al., 2003).

2. High Creek Fen

The most unique fen in the South Park basin is High Creek Fen, the most southern extreme rich fen in North America (Cooper, 1996), which is located on a 1500- acre privately-owned preserve in the southwest area of the South Park basin. The water chemistry and hydrology of High Creek Fen supports a unique diversity of flora and fauna, including three globally-rare and 10 state-rare plants, two globally-rare and 1 state-rare plant community, and one globally-rare invertebrate and 9 state-rare invertebrates (Brand and Carpenter, 1999). High Creek Fen was historically impacted by peat mining and cattle grazing, however the area is currently not impacted by such activities. However groundwater withdrawal projects associated with new housing developments may threaten the hydrologic and ecologic integrity of High Creek Fen. In 1991 the Nature Conservancy targeted High Creek Fen for preservation and research because it is a unique ecosystem, is relatively unaffected by environmental impacts. The Nature Conservancy is interested in identifying additional preservation lands to protect the hydrologic and ecologic integrity of High Creek Fen.

Previous research has found that there are no direct surface water inputs to High Creek Fen, and evaporative losses from the fen are twice as large as precipitation (Blanken unpublished data). Consequently groundwater must be the primary source of water to High Creek Fen. The source of groundwater to High Creek Fen has not been conclusively identified. Appel (1995), Johnson (1996) and Bruederle (1997) studied the groundwater features of the High Creek Fen area but neither study connected specific groundwater discharge or recharge areas with surface water in the fen and High Creek. Using water chemistry data from surface water in the fen, Cooper (1996) stated that there were three different groundwater sources. However, these data are not conclusive because the ion chemistry of water can change dramatically between the groundwater source and the surface water due to a variety of biologically- and chemically- mediated processes.

3. Research Justification

The goal of the research presented in the proceeding chapters is to characterize the seasonal variability in the hydrologic regime of High Creek Fen, as well as the water sources that maintain the hydrologic integrity of High Creek Fen. This research addresses important issues within the fields of hydrology and wetland conservation. There is compelling evidence that hydrologic regimes in watersheds throughout the western United States will shift during future decades due to global climate change (Smith, et al. 2003). Changes in local precipitation patterns and air temperature would likely have the greatest effect on High Creek Fen. Also, the location of a wetland ecosystem within the watershed and its connectivity to groundwater and surface water sources can determine how a wetland will respond to climatic and hydrologic changes (Pringle 2001). Thus, identifying the sources of water and the hydrologic regime of High Creek Fen under current climactic conditions will allow researchers to study how the hydrology of this unique fen ecosystem responds to future changes in the local climate system. In addition, information concerning the current sources of groundwater to the fen, the magnitude of groundwater discharge the fen receives from these sources across different seasons, and the interannual variability in the hydrologic regime of the fen could aid efforts to preserve the hydrology and ecology of High Creek Fen. For example, conservation managers may direct their efforts towards establishing additional preservation lands in the watershed to minimize groundwater withdrawls in the areas upgradient of High Creek Fen, thereby maintaining the primary source of water to the fen ecosystem.

The subsequent chapters of this thesis provide a more complete description of the hydrology and hydrochemistry of High Creek Fen. In Chapter 2, entitled ‘The groundwater hydrology of High Creek Fen’, physical hydrologic measurements and geospatial analysis show that there are two groundwater sources at High Creek Fen; the primary source originates to the northwest of the fen and a second source originates from the northeast of the fen. Also, groundwater hydrology is spatially and temporally variable at High Creek Fen during the study period, May 25, 2007 to May 28, 2008. Research findings in Chapter 3, ‘The hydrochemistry of High Creek Fen’, indicate that the variability in groundwater hydrology and hydrochemistry is driven by seasonal dynamics. In addition, the analysis of hydrochemical parameters, such as $\delta^{18}O$ and chloride concentration, shows that the western area of High Creek Fen is fed by the primary groundwater source to the fen, which originates to the northwest. These findings add to our understanding of the sources of groundwater to High Creek Fen. In addition, the data have generated additional hypotheses regarding the seasonally dynamic groundwater hydrology of the complex High Creek Fen ecosystem.

CHAPTER 2: Groundwater hydrology of High Creek Fen

1. Introduction

Hydrology shapes the structure and function of wetland ecosystems (Mitsch and Gosselink 2007). It is challenging, however, to characterize the hydrology of wetlands due to considerable spatial and temporal hydrologic variability. Nevertheless, wetlands' complex hydrologic regimes foster incredible chemical and biological diversity, and improve downstream water quality. The goal of the research presented in this chapter is to identify the groundwater sources to High Creek Fen, a unique wetland ecosystem, and to characterize the seasonal and interannual variability in hydrology at the fen.

Mineral-rich, groundwater-fed wetlands, known as fens, are diverse and unique aquatic ecosystems. South Park, a high elevation basin located in central Colorado, features at least 31 rich and extremely rich fens, a distinction attributed to soils with a high pH and high calcium and magnesium concentrations (Cooper and Sanderson 1997; Cooper 1996). The most unique of these is High Creek Fen, the most southern extreme rich fen in North America, located on a privately-owned preserve at the southwest corner of the South Park basin (Figure 1). High Creek Fen supports a unique diversity of flora and fauna, including three globally-rare and 10 state-rare plants, two globally-rare and 1 state-rare plant community, and one globally-rare invertebrate and 9 state-rare invertebrates (Brand and Carpenter 1999). Land use changes in South Park, such as new housing developments, may threaten this rare ecosystem by exacerbating groundwater resource issues in an already water-limited region. Research describing the groundwater hydrology of High Creek Fen is necessary to understand how groundwater withdrawals in the region may influence the hydrologic and ecologic integrity of High Creek Fen.

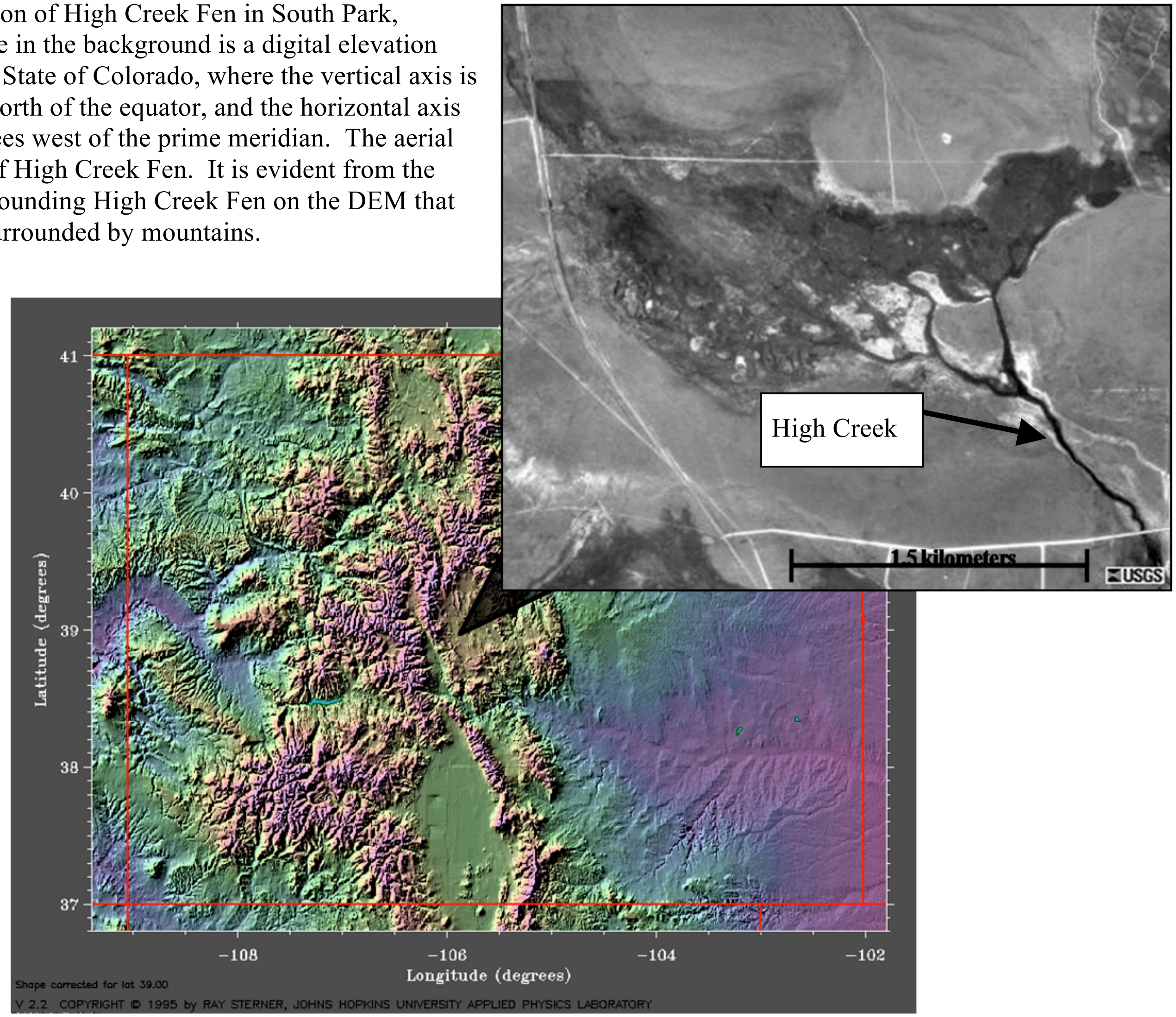


Figure 1. The location of High Creek Fen in South Park, Colorado. The figure in the background is a digital elevation model (DEM) of the State of Colorado, where the vertical axis is latitude, in degrees north of the equator, and the horizontal axis is longitude, in degrees west of the prime meridian. The aerial photo is a close-up of High Creek Fen. It is evident from the high relief areas surrounding High Creek Fen on the DEM that High Creek Fen is surrounded by mountains.

Previous research has described some aspects of the hydrogeology and geochemistry of High Creek Fen. Hydrologic data collected from 2000 to 2004 suggests that groundwater discharge is the primary source of water to High Creek Fen (Table 1; Blanken unpublished data). Two different hydrogeologic studies suggest that there are multiple groundwater discharge locations throughout the fen (Appel 1995; Johnson 1996) however, the studies do not agree on the discharge locations. In addition, previous research suggests that there are multiple groundwater sources to High Creek Fen since there is spatial variability in the groundwater dynamics and surface water chemistry throughout the fen (Appel 1995; Johnson 1996; Cooper 1996). There are many inconsistencies between the afore-mentioned studies and as a result, the hydrologic regime of High Creek Fen is not understood.

The goal of this thesis chapter is to produce a more complete description of the hydrologic system at High Creek Fen. The research presented in this chapter was designed to test the hypothesis that the hydrology of High Creek Fen is fed by one, shallow groundwater source originating in northwest of High Creek Fen at Warm Springs Fen (Figure 2). This hypothesis was formulated based on topographic and hydrologic evidence; land elevation contours decrease from the northwest to the southeast of High Creek Fen, and an ephemeral creek channel courses from Warm Springs Fen area to Highway 285 directly west of High Creek Fen. Physical hydrologic measurements and geospatial analysis were used to evaluate the validity of this hypothesis.

Table 1. Water budget estimates for 200-2004, based on precipitation and evaporation measurements at High Creek Fen, suggest that groundwater inputs provide between 19 and 411 mm of water to the fen annually (Blanken unpublished data). P stands for precipitation, E stands for evaporation, ΔS stands for change in soil moisture and R stands for run-off. The run-off (R) values in this table are negative and thus represent the amount of groundwater, in millimeters, required to balance the water budget at High Creek Fen.

Year (period)	*P* (mm) 257 mm ('61-'04)	*E* (mm)	*E* / *P*	Δ*S* (mm)	*R* (mm)
2000 (162-366)	147	365	2.48	13	-231
2001 (1-34; 168-365)	139	251	1.81	51	-163
2002 (1-365)	188	151	0.80	56	-19
2003 (1-365)	158	513	3.25	56	-411
2004 (1-366)	206	536	2.60	52	-382

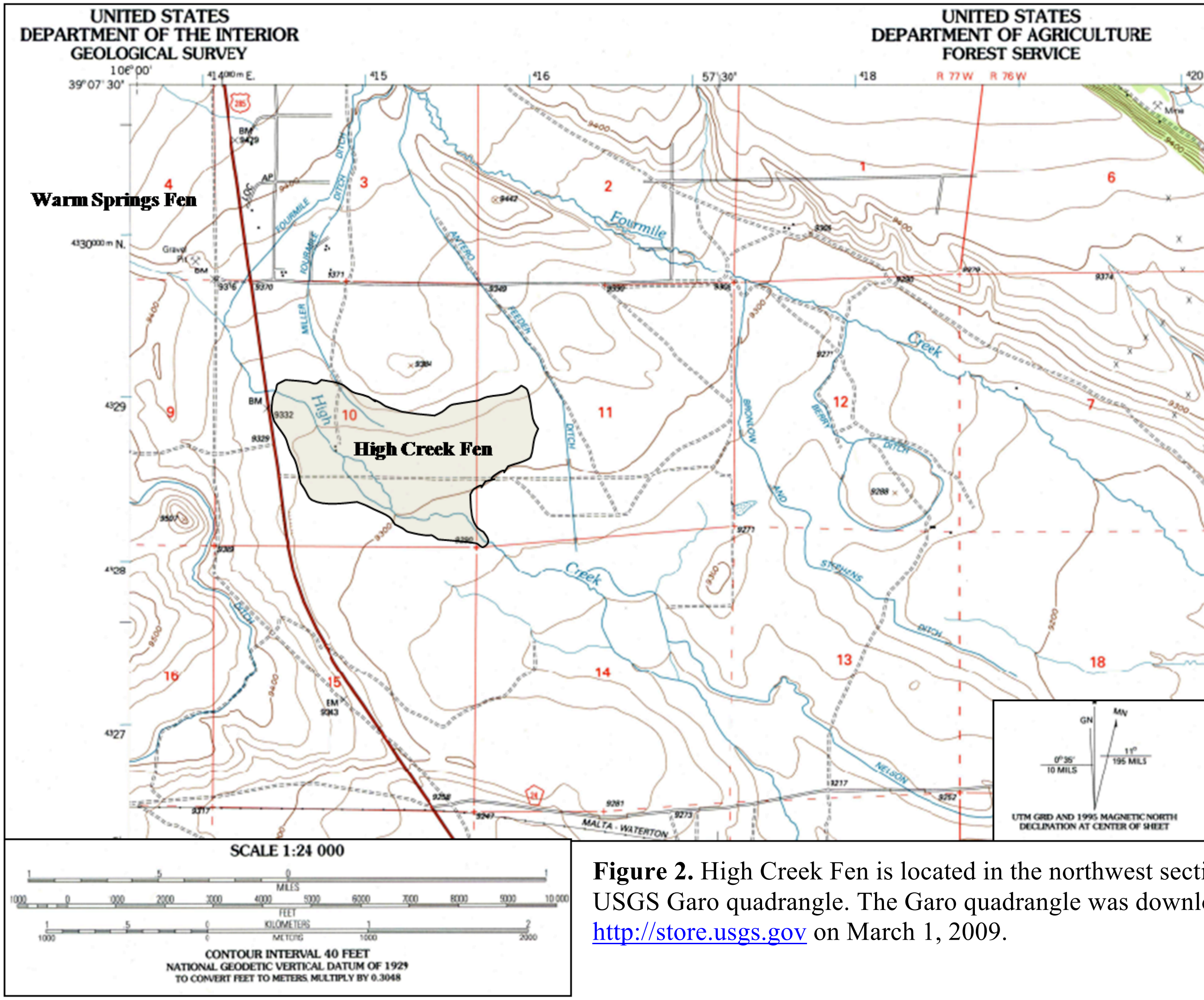


Figure 2. High Creek Fen is located in the northwest section of the USGS Garo quadrangle. The Garo quadrangle was downloaded from http://store.usgs.gov on March 1, 2009.

2. Material and Methods

2.1 Study Site

High Creek Fen is a 750-acre wetland area located in the western edge of the South Park basin, approximately 2830 meters above sea level. South Park is underlain by Tertiary sedimentary rock and Quaternary glacial alluvium and outwash sediments (Chapman et al. 2002; Johnson and Steingraeber 2003), and is bordered by the Kenosha and Tarryall Ranges to the north, the Mosquito Range to the west and the Elkhorn Thrust Fault to the east. Johnson and Steingraeber (2003) and Chapman et al. (2003) suggest that the prevalence of nutrient-rich, calcareous fens in the South Park basin is due the combined effect of limestone and dolomite sediments derived from the Mosquito Range and the extensive faulting associated with the Elkhorn thrust fault. Nonetheless, these geologic phenomena influence groundwater and surface water hydrology, and hydrochemistry within the South Park basin. The South Park basin is primarily drained by the South Platte River, of which High Creek, the stream that drains High Creek Fen, is a tributary. The headwaters of High Creek are located northwest of High Creek Fen, at the eastern edge of the Mosquito Range. High Creek flows intermittently before going subsurface northwest of High Creek Fen, possibly due to surface water recharge of the shallow groundwater system or upstream surface water diversions (Brand and Carpenter 1999). Consequently, there are no surface water inputs to High Creek Fen, however, High Creek flows perennially from the outlet of the fen to its confluence with the Fourmile Creek.

2.2 Hydrologic Measurements

In order to characterize groundwater hydrology at High Creek Fen, five nests with three piezometers (screen depths of 0.6 meters (m), 0.9 m and 1.2-m below ground surface (bgs)) and a groundwater well (screened from 1.2 m to 0 m below ground surface) were installed at locations throughout the study site on May 19, (Nest 1); May 20, (Nest 5); May 24, (Nest 2); May 29, (Nest 3); May 30, (Nest 4) 2007 (Figure 3). A sixth nest, which included two piezometers (screen depths of 0.6 m and 0.9 m bgs) and a groundwater well (screened from 0.9 m to 0 m bgs), was installed on May 28, 2007 (Nest 6) in a region with a shallower bedrock depth. Piezometers and wells were constructed from 1- inch (internal diameter) PVC pipe and wire-mesh screen (0.01 inch openings). Piezometers were constructed with a 3-centimeter (cm) screened opening at the base, whereas groundwater wells were constructed with 3-cm screened openings every 10 cm from the base to the ground surface. Boreholes (1.5 to 2.0 inches in diameter) for each piezometer and well were hand-dug using an auger. After each piezometer and well was placed in the hole, the remaining area around the PVC pipe was filled with excavated soil from High Creek Fen.

Hydraulic head in piezometers and groundwater level in groundwater wells was manually measured using an electric measuring tape at each nest 16 times between May 30, 2007 and May 29, 2008. Each piezometer and well was installed so that approximately 30 cm of additional PVC pipe rose above the ground surface. This section of the piezometer or well, called the riser height, was measured during installation in May 2007; on November 4, 2007; and on May 3, May 9, May 21, and May 28, 2008. The riser height was re-measured on the afore-mentioned dates in order to monitor freeze-thaw activity that would influence the accuracy of hydraulic head and groundwater table measurements. Hydraulic conductivity of the groundwater aquifer at a depth of 1.2 meters at each of the six installed piezometer nest sites was measured in situ with a Guelph constant-head field permeameter (Model 2800) on

Figure 3. The locations of the six installed groundwater nests at High Creek Fen.

May 20, 2008. In addition, groundwater level measurements were collected from 18 groundwater wells installed during previous research studies. Measurements at these additional groundwater wells were collected on five days during the study period: June 20, 2007; September 2, 2007; November 4, 2007; May 3, 2008; May 29, 2008. The groundwater hydraulic head and elevation measurements were paired with stream velocity measurements, collected using a current meter on May 20, May 25, May 29, June 8, June 20, 2007, and the surface- float velocity method, as described in Dingman (2002), on July 29, August 16, August 22, September 2, September 27, and November 4, 2007, and May 3, May 8, May 9, May 16, May 21, and May 29, 2008 at High Creek, the outlet of the fen (Figure 3). Precipitation data were downloaded from the Antero Reservoir weather station located 10 kilometers south of the study site (data accessed at http://weather-warehouse.com/WxHubP/WxSPM71371262372_71.237.94.104/2_Antero_Reservoir.html).

2.3 Data Analysis

2.3.1 Time Series and Statistical Analysis

In the field, hydraulic head (h) and elevation head (z) of the groundwater were measured. Using these measurements, pressure head ($P/\rho_w g$) was calculated using the Bernoulli equation (1).

$$\frac{P}{\rho_w g} = h - z \tag{1}$$

The pressure head of the water, $P/\rho_w g$, includes P, the pressure exerted by the water column (m/LT^2); ρ_w is the fluid density (m/L^3), and g is gravitational acceleration (L/T^2) (Figure 4). Vertical hydraulic gradients were calculated by taking the difference between the shallowest piezometer (A, 0.6 m bgs) and the deepest piezometer (C, 1.2 m bgs at Nests 1-5; B, 0.9 m bgs at Nest 6). Positive vertical hydraulic gradients indicate upward groundwater flow, also known as groundwater discharge, and negative vertical hydraulic gradients indicate downward groundwater flow, or groundwater recharge. Statistical parameters such as mean, median, range, standard deviation and Pearson's correlation coefficients using a two-tailed test of significance were calculated for the groundwater hydraulic head, groundwater table elevation, stream discharge and precipitation time series data using the Descriptive Statistics module in OriginPro 8 (OriginLab Corporation 2008).

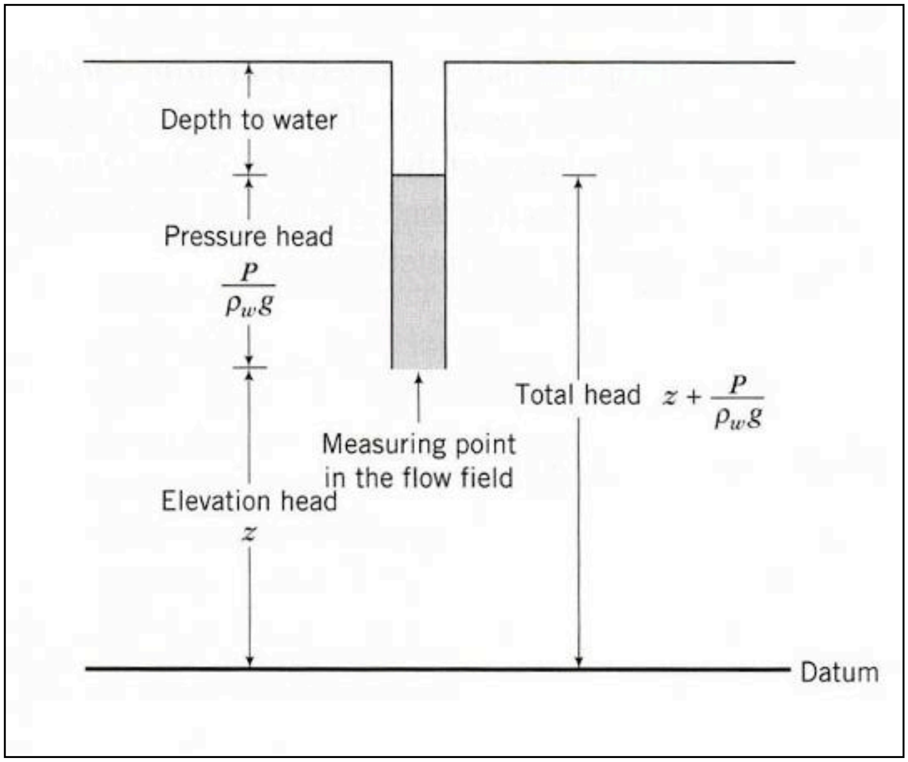


Figure 4. A graphical representation of the variables used to calculate $P/\rho_w g$ in the Bernoulli equation. From Schwartz and Zhang 2003.

2.3.2 Geospatial Analysis

Groundwater elevation contour maps and kriging prediction maps were generated from groundwater elevation data collected on June 20, 2007; September 2, 2007; November 4, 2007; May 3, 2008; May 29, 2008. This research utilized the interpolation methods Inverse Distance Weighted (IDW) interpolation and Kriging in the Spatial Analyst toolbox of ArcMap, ArcView 9.2 (ESRI 2006). Using IDW, groundwater elevations at unsampled locations were estimated using the equation,

$$Z_j = \frac{\sum \frac{Z_i}{d^n{}_{ij}}}{\sum \frac{1}{d^n{}_{ij}}} \tag{2}$$

where Z_j is the estimated groundwater elevation at location j, d_{ij} is the distance from a sampled location i to the unsampled location j, Z_i is the measured groundwater elevation at location i, and n is a user-defined exponent term which influences the topography of the interpolated surface; a larger n results in more topographic detail around sampled values than unsampled values (Figure 5; Bolstad 2005). In this research, n values were optimized through trial and error; $n=2$ was found to be the optimal value for this work. Whereas IDW was used to estimate groundwater elevation at unsampled locations based on the distance between the measured data point and the predicted data point, ordinary kriging considered the spatial autocorrelation between the measured data points, and spatial trends to generate groundwater elevation estimations at unsampled locations (Bolstad 2005). Prior to generating a prediction map, semivariogram models were calculated to evaluate the spatial autocorrelation between measured points (3). Semivariogram models calculate semivariance of predicted groundwater elevations with increasing distance from groundwater elevation at the sampled location.

$$Semivariogram(distance\ \boldsymbol{h}) = 0.5 * average\ [(value\ at\ location\ \boldsymbol{i} - value\ at\ location\ \boldsymbol{j})^2] \tag{3}$$

Kriging prediction maps were generated for each date upon which groundwater elevation data were collected (June 20, 2007; September 2, 2007; November 4, 2007; May 3, 2008; May 29, 2008) based on spherical, exponential, linear, circular and Gaussian semivariogram models.

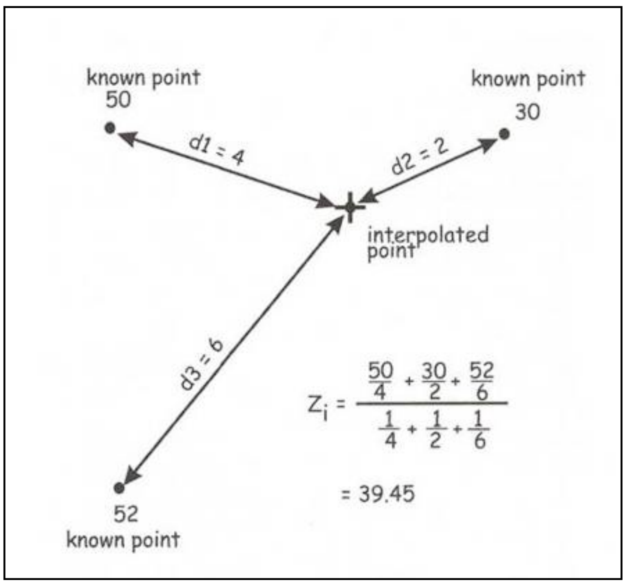


Figure 5. A graphical example of the IDW interpolation method. From Bolstad 2005.

3. Results

3.1 Hydrologic Measurements

Groundwater hydraulic heads and groundwater discharge displayed spatial and temporal variability at High Creek Fen during the May 30, 2007 to May 29, 2008 study period (Figure 6). The general direction of groundwater flow at High Creek Fen was from north/northwest to east/southeast (Figures 7, 8 and 9). This general pattern was consistent throughout the study period however, groundwater dynamics were temporally variable on smaller spatial scales. As shown in Figure 6, in the northwest area of High Creek Fen (Nest 1) groundwater hydraulic heads were high in May 2007 and May 2008 following snowmelt. In this area, hydraulic heads decreased through the summer season into mid-September, 2007 and then rose again in November 2007. In contrast, hydraulic heads were high in the northeast corner of the fen (Nest 5) through the summer season, increasing from July to September 2007, but were then lower in November 2007. Hydraulic heads in the southern region of High Creek fen (Nests 4 and 6) were more temporally consistent than other areas of the fen, excluding hydraulic head measurements on May 30, 2007 (Figure 6). Generally, groundwater in the north and northwest areas of High Creek Fen (Nests 1 and 3) demonstrated the greatest range in hydraulic heads over the study period, at all depths (Figure 10 and Table 2). Groundwater hydraulic heads in the south and southeast and east (Nests 4, 5 and 6, respectively) were less variable over the study period.

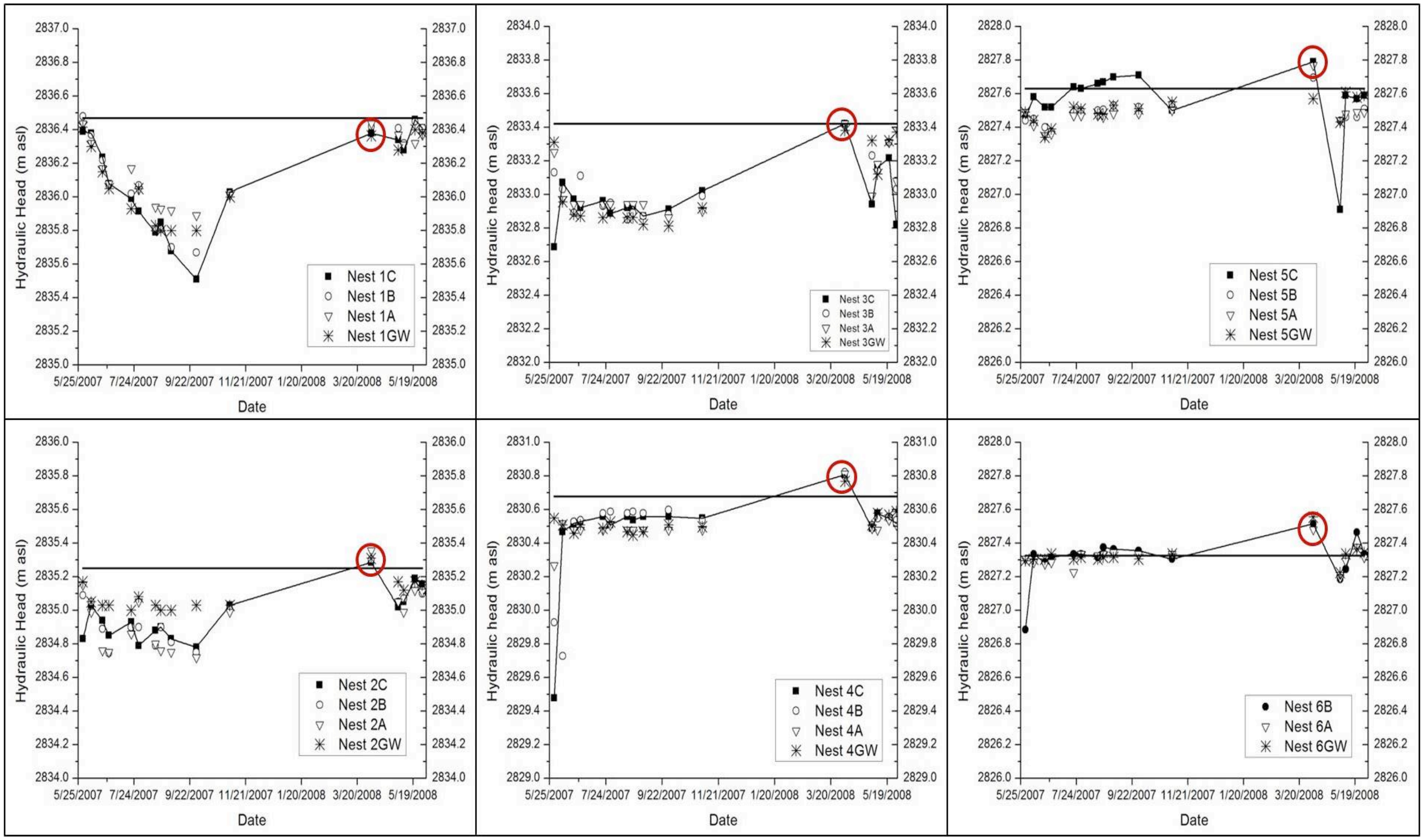


Figure 6. Hydraulic head and groundwater table measurements collected May 30 2007 through May 29 2008 at the six installed nests, High Creek Fen. Red circles indicate that the groundwater was frozen at during this collection period. Hydraulic head measurements for Nests 3, 4 and 6 on May 30, 2007 may not reflect actual conditions because the piezometers and nests were installed right before the measurements. The ground surface on each plot is indicated by the horizontal black line.

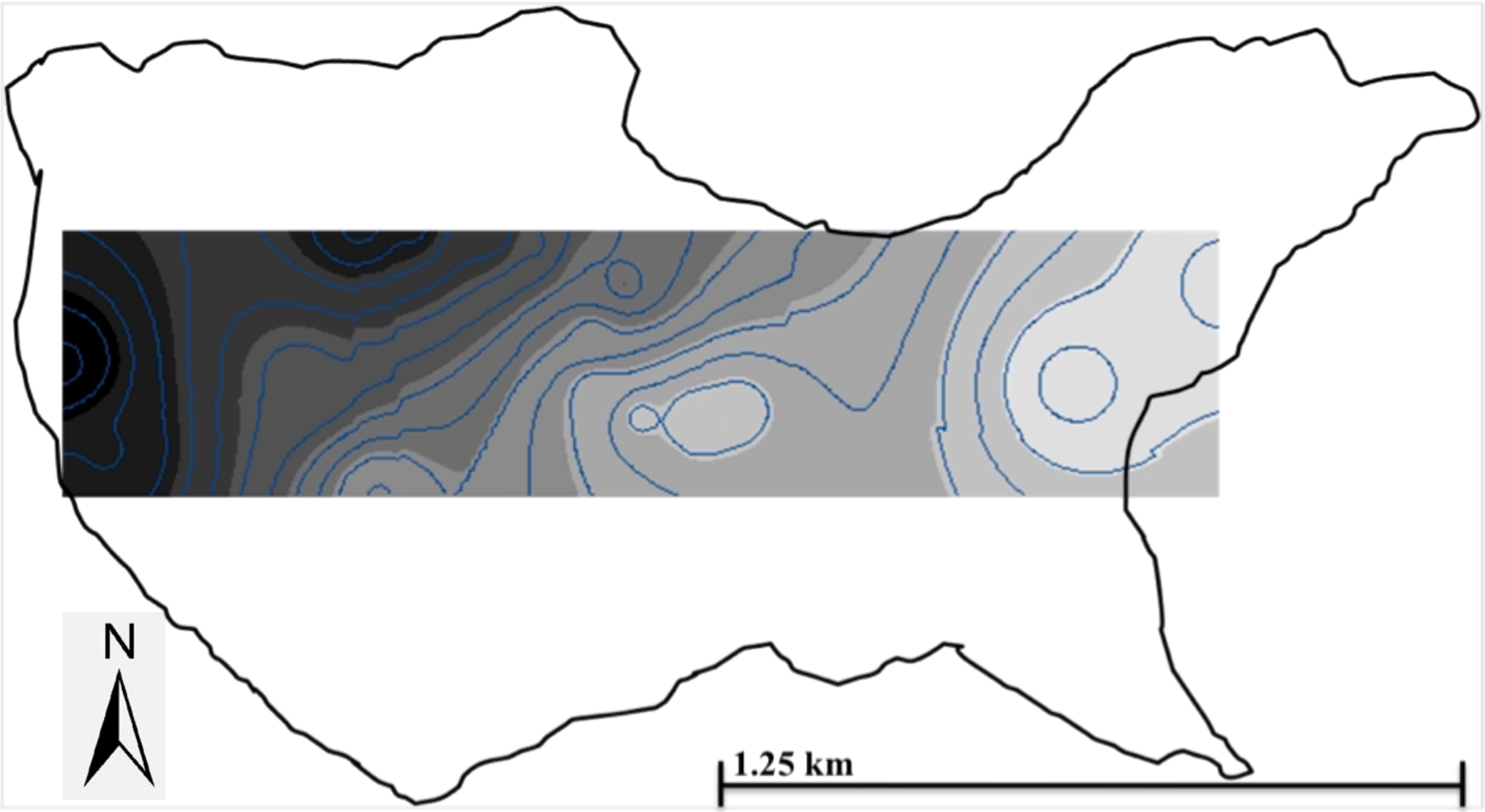
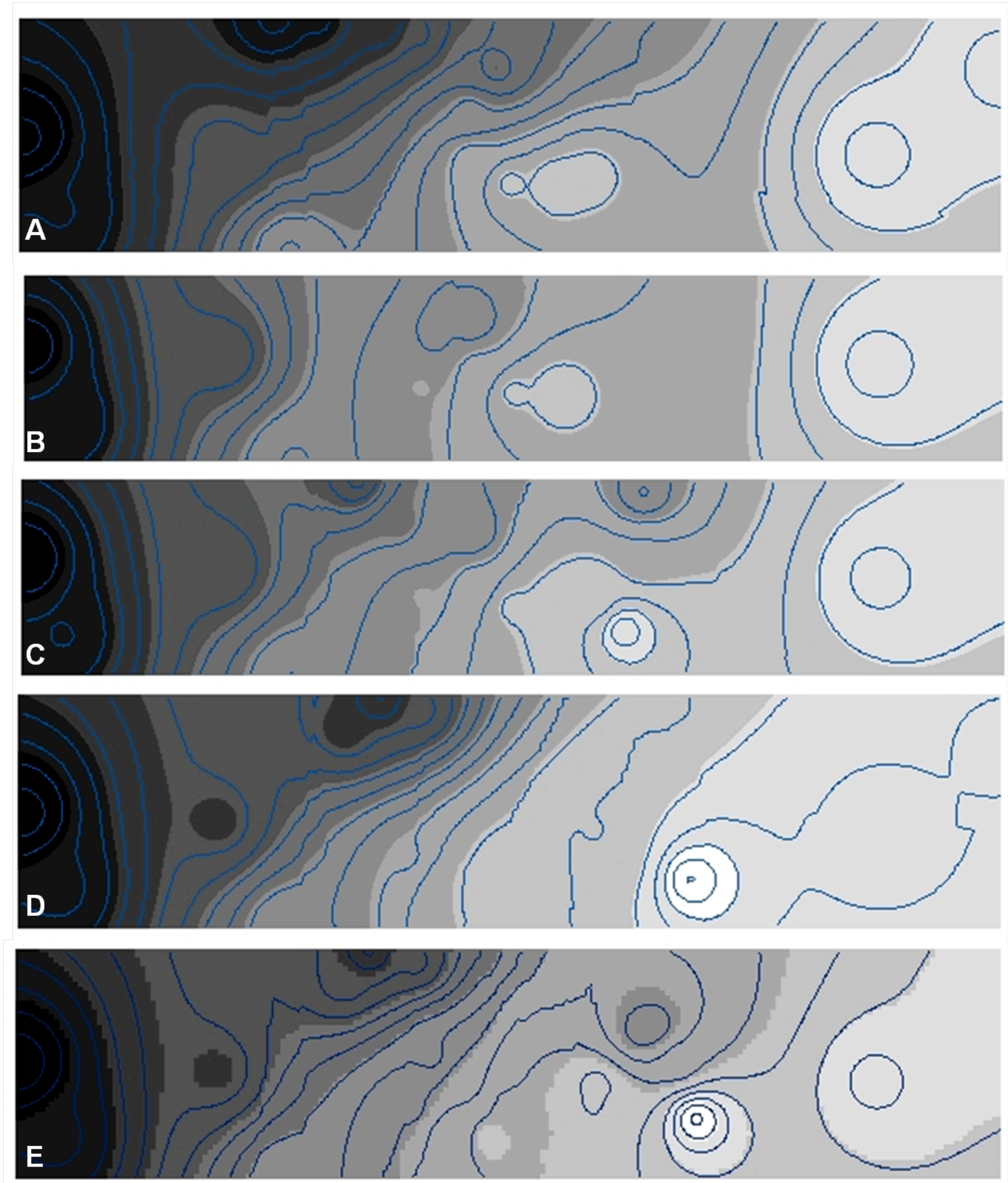


Figure 7. An approximate georeference for groundwater elevation contour maps and kriging maps of High Creek Fen. The length of the rectangular map is 1.2 km. Contour intervals are 0.5m.



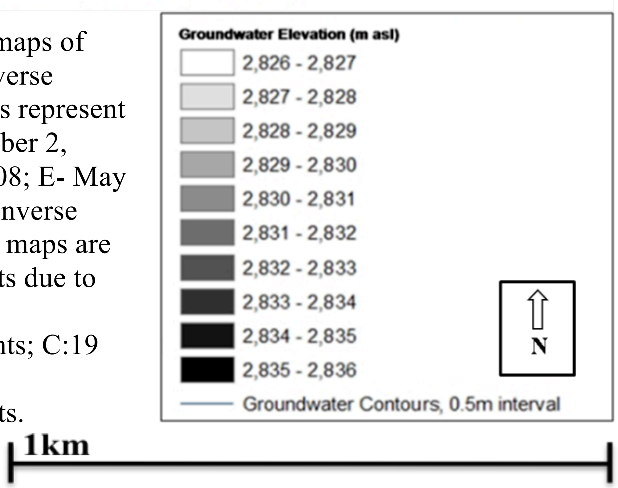


Figure 8. Groundwater elevation contour maps of High Creek Fen were generated through inverse distance weighting (IDW) in ArcMap. Maps represent 5 time points: A- June 20, 2007; B- September 2, 2007; C- November 4, 2007; D- May 3, 2008; E- May 29, 2008**.** The maps were generated using inverse distance weighting (IDW) in ArcMap. The maps are based on different numbers of measurements due to sampling inconsistencies.A:17 locations/ measurements; B: 14 locations/measurements; C:19 locations/ measurements; D: 19 locations/ measurements; E:24 locations/measurements.

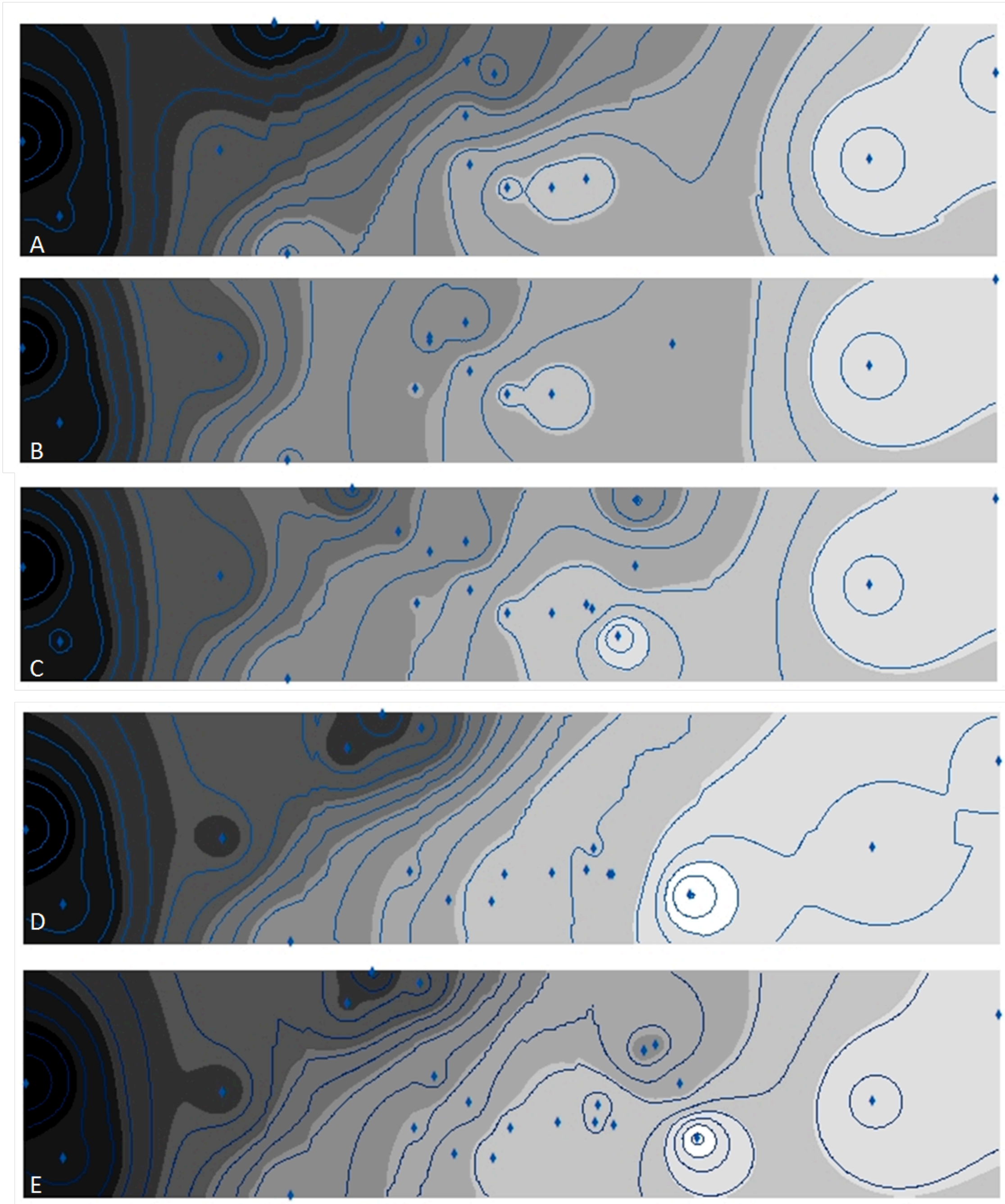
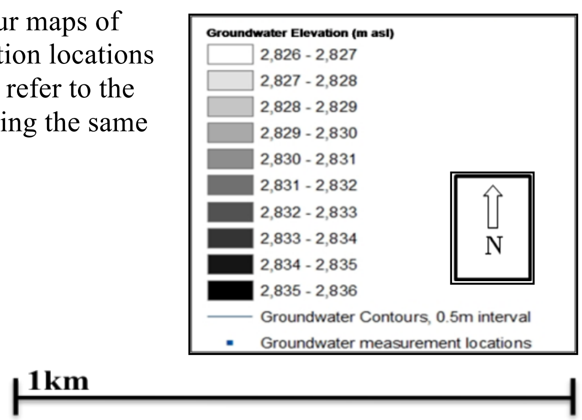


Figure 9. Groundwater elevation contour maps of High Creek Fen showing the data collection locations for each of the 5 time points. Maps A-E refer to the same time points, and were generated using the same methods as those featured in Figure 8**.**



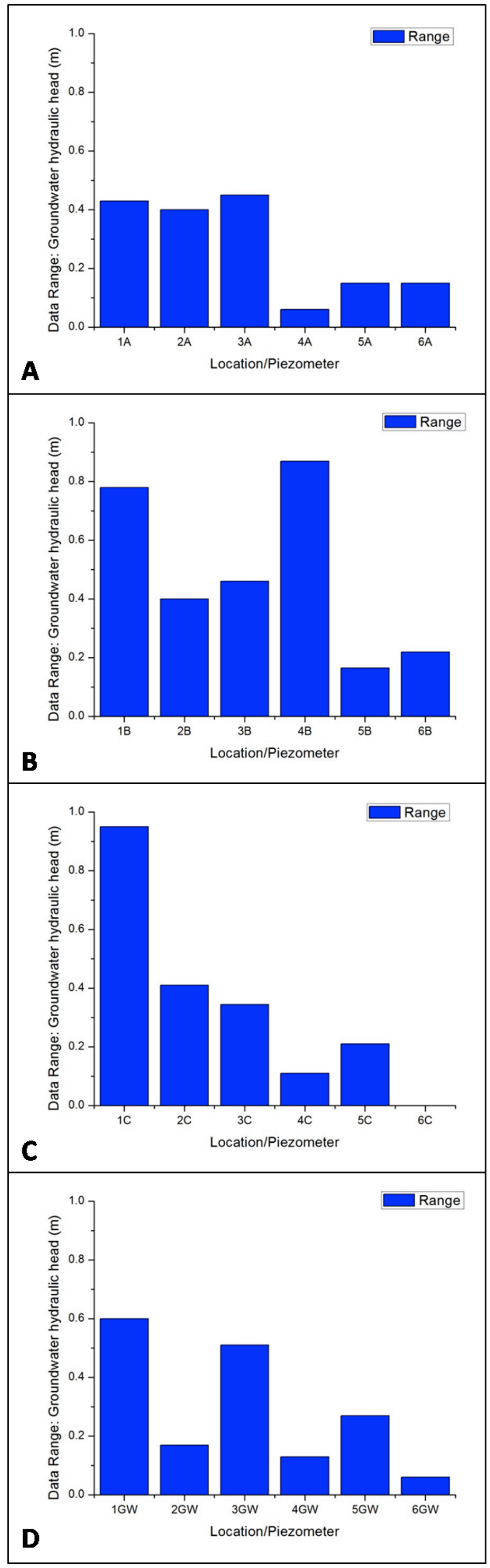


Figure 10. The range in groundwater hydraulic heads at each location and depth over the study period at High Creek Fen. Data values on May 30, 2007 were eliminated because measurements were made soon after piezometer and well installation. Data values from April 4, 2008 were eliminated because groundwater at all locations was frozen.

Table 2. Descriptive statistics tables for the three depths of piezometers and the groundwater wells at the installed nests at High Creek Fen. Data values on May 30, 2007 were eliminated because measurements were made soon after piezometer and well installation, and may not reflect actual conditions. Additionally, data values from April 4, 2008 were eliminated because groundwater at all locations was frozen.

Hydraulic Heads (HH; m asl)	**Nest 1B**	**Nest 2B**	**Nest 3B**	**Nest 4B**	**Nest 5B**	**Nest 6B**
Mean of HH data collected during the study period	2836.17	2834.95	2833.03	2830.50	2827.48	2827.32
Median of HH data	2836.17	2834.99	2832.94	2830.48	2827.47	2827.32
Range in HH data	0.55	0.63	0.56	0.55	0.42	0.29
standard deviation of HH data	0.20	0.19	0.17	0.10	0.09	0.06

Hydraulic Heads (HH; m asl)	**Nest 1A**	**Nest 2A**	**Nest 3A**	**Nest 4A**	**Nest 5A**	**Nest 6A**
Mean of HH data collected during the study period	2836.17	2834.95	2833.03	2830.50	2827.48	2827.32
Median of HH data	2836.17	2834.99	2832.94	2830.48	2827.47	2827.32
Range in HH data	0.55	0.63	0.56	0.55	0.42	0.29
standard deviation of HH data	0.20	0.19	0.17	0.10	0.09	0.06

Hydraulic Heads (HH; m asl)	**Nest 1C**	**Nest 2C**	**Nest 3C**	**Nest 4C**	**Nest 5C**
Mean of HH data collected during the study period	2836.11	2834.97	2832.98	2830.48	2827.56
Median of HH data	2836.16	2834.93	2832.94	2830.54	2827.59
Range in HH data	0.95	0.51	0.73	1.33	0.88
standard deviation of HH data	0.30	0.15	0.17	0.28	0.20

Hydraulic Heads (HH; m asl)	**Nest 1GW**	**Nest 2GW**	**Nest 3GW**	**Nest 4GW**	**Nest 5GW**	**Nest 6GW**
Mean of HH data collected during the study period	2836.10	2835.09	2833.03	2830.53	2827.50	2827.33
Median of HH data	2836.05	2835.04	2832.91	2830.51	2827.51	2827.31
Range in HH data	0.62	0.31	0.57	0.32	0.27	0.33
standard deviation of HH data	0.24	0.09	0.22	0.08	0.07	0.07

As shown in Figure 11, groundwater discharge and recharge patterns varied between piezometer nest locations. Whereas groundwater discharged to surface water in the south, southeast and northeast areas of High Creek Fen (Nests 4, 5 and 6) throughout the study period, vertical groundwater flow in the north and northwest (Nests 1 and 3) varied between recharge and discharge. Pearson correlation coefficients and corresponding p values calculated on timeseries data showed that there was no statistically significant correlation between groundwater hydraulic heads or groundwater table elevations and stream discharge or precipitation patterns (Figure 12; statistical analysis results are not shown). However, there was a statistically significant correlation between groundwater hydraulic heads at Nest 1 at a depth of 1.2 m (piezometer C) and hydraulic heads at 0.6 and 0.9 m (piezometers A and B) over the study period. At Nest 1, hydraulic heads at piezometer C were significantly correlated to groundwater table elevation patterns. In addition, hydraulic heads at Nest 6 at 0.9 m depth (piezometer B) were significantly correlated with hydraulic heads at Nest 4 at 0.6 m depth (piezometer A). With the exception of the afore-mentioned correlations, groundwater dynamics were spatially variable at the monitored locations within High Creek Fen.

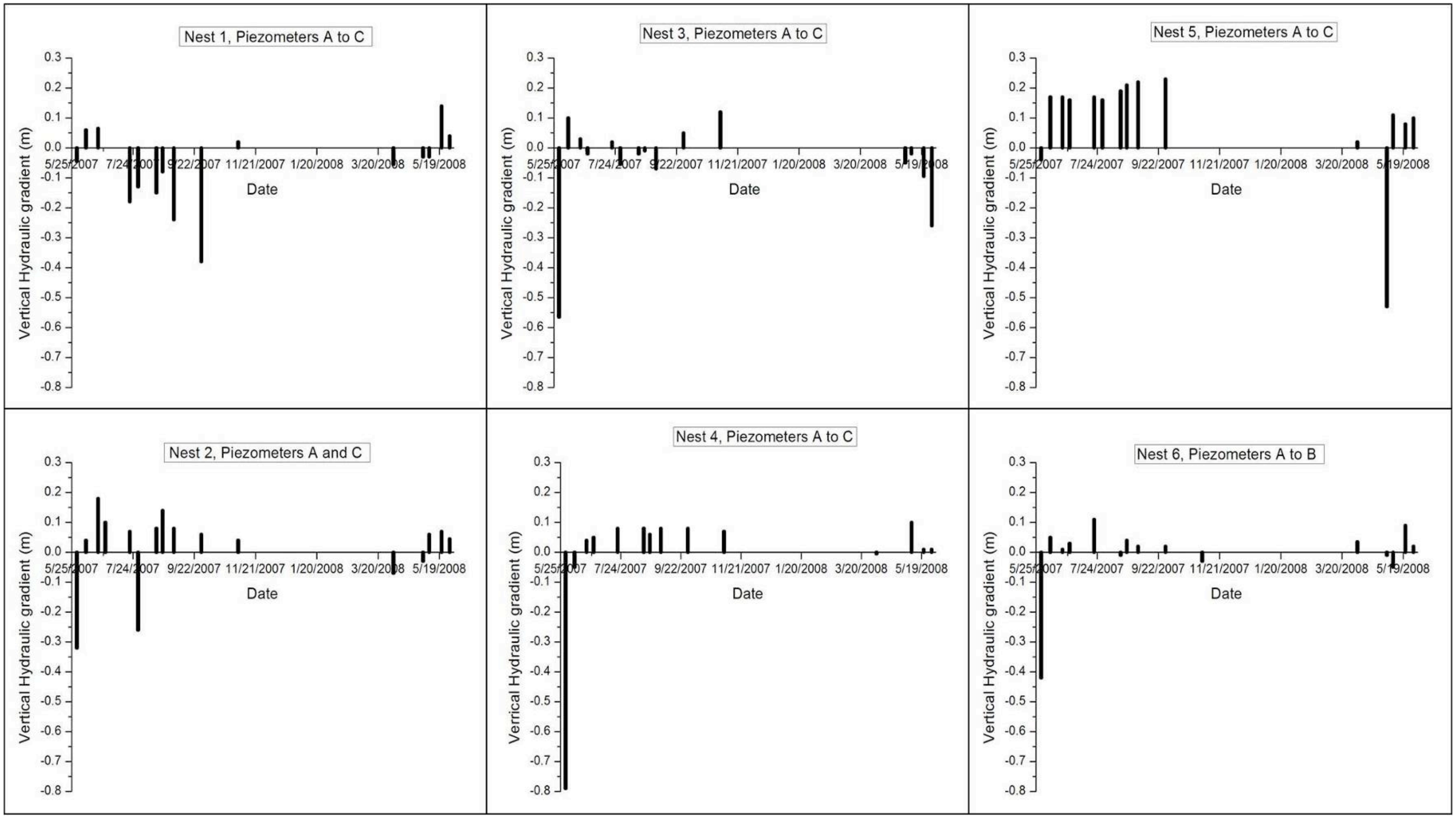


Figure 11. The vertical direction of groundwater flow at each installed piezometer nest. Positive values indicate groundwater discharge into the surface water whereas negative values represent recharge to the groundwater aquifer.

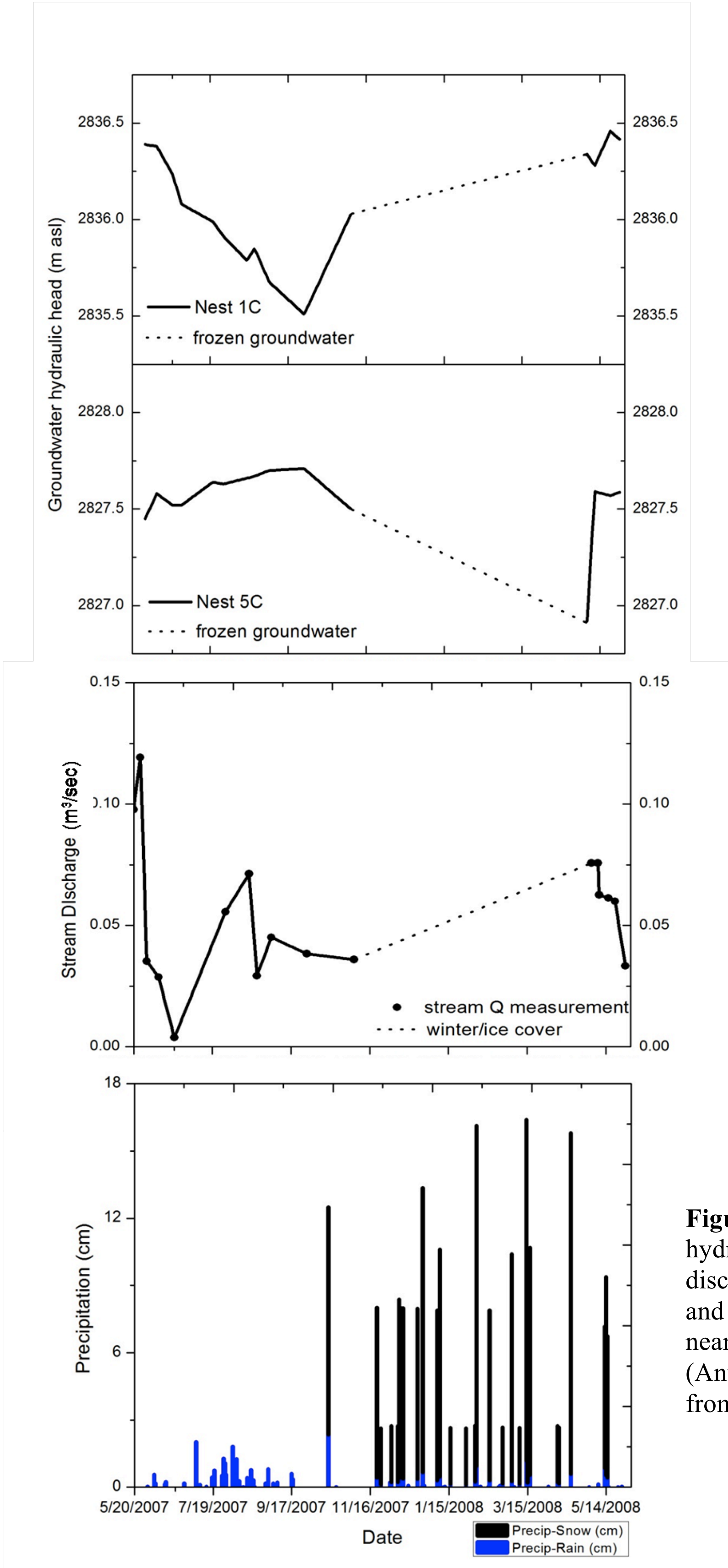


Figure 12. Groundwater hydraulic heads, stream discharge at High Creek, and precipitation from a nearby weather station (Antero Reservoir, 10 km from High Creek Fen).

3.2 Hydraulic Conductivity

Saturated hydraulic conductivity (K) at High Creek Fen was measured on May 20, 2008 at each of the six installed piezometer nests. Results from these measurements indicate that there is a large amount of spatial variability in K at High Creek Fen. For example, Nest 1, located in the northwestern region of High Creek Fen, had the highest K whereas the K measured at Nest 3, located directly east of Nest 1, was more than an order of magnitude greater (Table 3 and Figure 13). Nest 2, in the southwest region of High Creek Fen, also had a relatively high K value. K at Nest 4 was similar to that measured at Nest 1. Measured K values at Nests 5 and 6, the installed nests in the eastern region of the fen, were more similar to one another than to any of the other measured values.

Table 3. Hydraulic conductivity (K) was measured using a field permeameter on May 20, 2007. Displayed K values represent an average of rates recorded every two to five minutes over a 30- minute period.

	Nest 1	**Nest 2**	**Nest 3**	**Nest 4**	**Nest 5**	**Nest 6**
Hydraulic Conductivity (m/day)	2.70	22.77	33.04	3.98	8.11	9.50

Figure 13. Hydraulic conductivity (K) values measured on May 20, 2008 at each installed piezometer nest location.

3.3 Geospatial Analysis: Groundwater Elevation

As shown in Figures 8, 9 and 14, the general groundwater flow direction at High Creek Fen was from northwest to southeast. This general pattern did not display temporal variation. Although groundwater levels within local areas of High Creek Fen varied temporally over the course of the study period, these variations were not significant enough to alter the net direction of groundwater flow across seasonal scales at High Creek Fen. In addition, groundwater levels across High Creek Fen mirror ground surface elevations. Ground surface elevation differences across the fen are greater in magnitude than variations in groundwater levels across the study period.

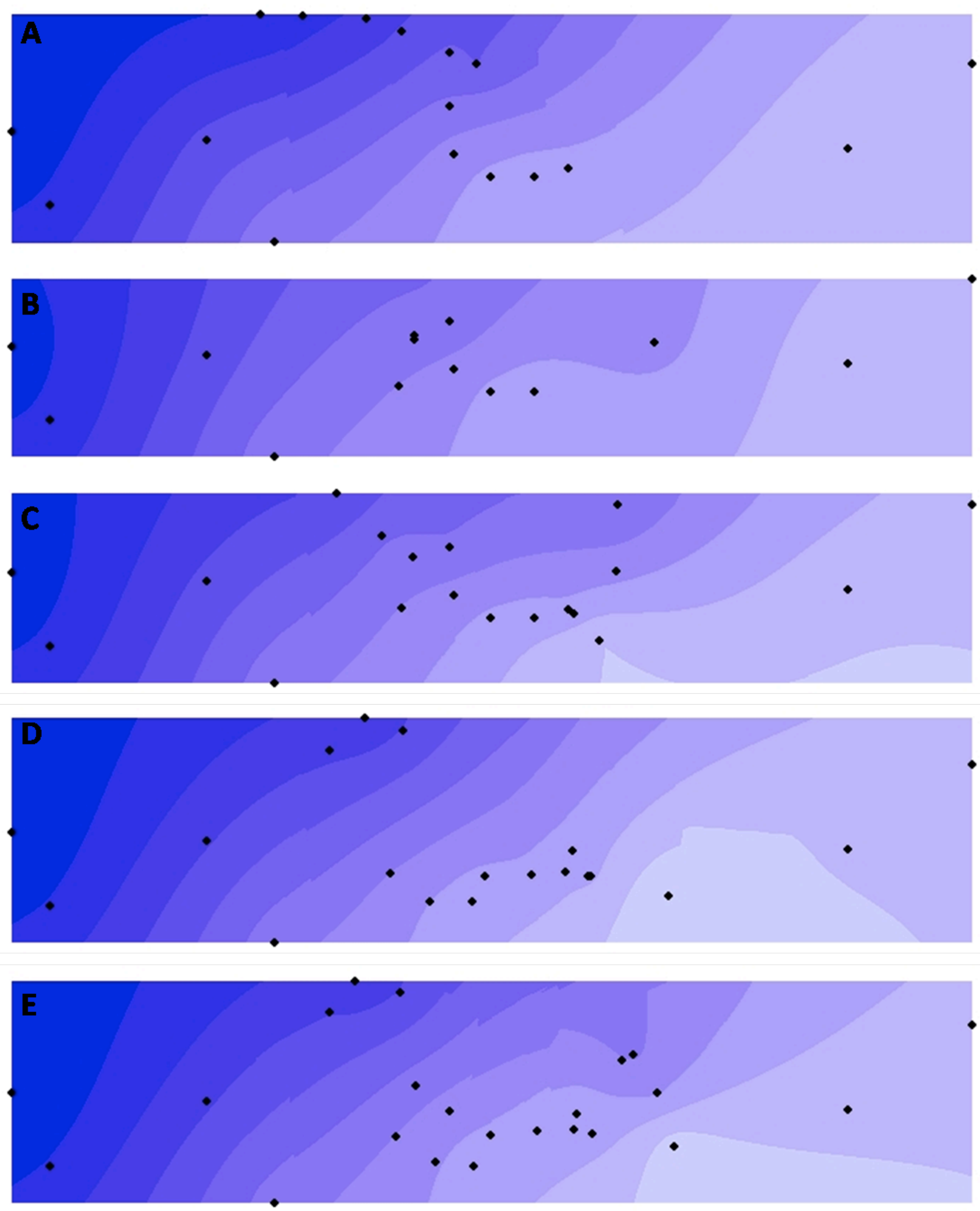
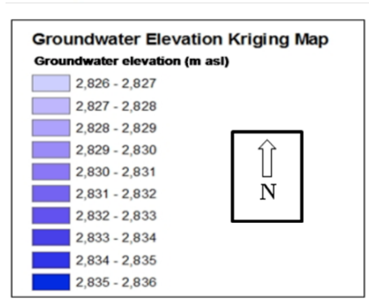


Figure 14. Groundwater elevation maps of High Creek Fen were generated using Ordinary Kriging with a spherical variogram model in ArcMap. Data points and time periods are the same as those used to generate Figure 8.



4. Discussion

This primary hypothesis of this research is that High Creek Fen was fed by a single, shallow groundwater source. Results from geospatial analysis support this hypothesis by showing that the net direction of groundwater flow at High Creek Fen is consistent across seasonal gradients. However, finer-scale analyses, such as the analysis of groundwater hydraulic head data and discharge time series data, suggest that the groundwater dynamics at High Creek Fen are spatially and temporally variable and that two different sources feed groundwater at High Creek Fen.

Groundwater hydraulic head time series (Figure 6) show the contrast between groundwater dynamics in the northwest region (Nest 1) and the northeast region (Nest 5) of High Creek Fen. Although statistical analysis of groundwater hydraulic head data did not reveal any significant relationships between nest locations, the variations in hydraulic heads at Nests 1, 2 and 3 follow similar patterns across the study period whereas groundwater dynamics at Nests 5 and 6 are similar to one another. The hydraulic heads at Nest 4 follow a similar pattern to hydraulic heads at Nests 5 and 6, however, this is an unexpected finding since Nest 4 is located on the west side of the fen (Figure 3). Groundwater discharge data also demonstrate the differences in groundwater dynamics between the northwest and northeast regions of High Creek Fen. Whereas groundwater recharge to the aquifer is the dominant process throughout the study period at Nest 1, groundwater discharge to surface water is the dominant process at Nest 6. These data suggest that the northwest region of High Creek Fen is fed by one groundwater source, such as groundwater originating from Warm Springs Fen, whereas the northeast region is fed by a difference source, potentially groundwater from the east of High Creek Fen such as the Fourmile Creek drainage.

Results from the hydraulic conductivity study show that shallow aquifer properties are spatially heterogeneous (Table 3; Figure 13). Hydraulic conductivity measured at the installed nest locations can be divided into three groups; low conductivity (Nest 1 and 4), moderate conductivity (Nests 5 and 6), and high conductivity (Nests 2 and 3). Since hydraulic conductivity measures how easily water flows through the aquifer material, this information describes another important characteristic of groundwater flow at High Creek Fen. The variability in the hydraulic conductivity measurements could be the result of factors such as the spatial variability in soil texture, soil moisture and soil temperature across the measurement locations at High Creek Fen; the time of day at which the measurements were taken; and technical difficulties with properly operating the constant-head field permeameter. However, the spatial heterogeneity in K at High Creek Fen is consistent findings of similar studies in fen environments. Recent studies have published shallow groundwater K values which range by two orders of magnitude or more within a study site (Rosa and Larocque 2008; Strack et al. 2008; Hogan, et al. 2006). Rosa and Larocque (2008) reported K values between 9.9×10^{-3} and 5.5 m/day for a groundwater in the Lanoraie fen complex, and Strack, et al. (2008) and Hogan, et al. 2006 reported K values that ranged from 8.6×10^{-4} to 8.6×10^{-2} m/day within northern peatlands.

The geospatial analysis of groundwater elevation data describes more general groundwater dynamics at High Creek Fen. Since groundwater elevation sampling was not consistent across the data collection points, it is not possible to identify temporal changes in groundwater flow. However, it is clear that the general groundwater flow direction is north/northeast to east/southeast. General groundwater elevation contours follow land surface contours, which is consistent with a shallow groundwater source. A sampling scheme that was temporally consistent might identify additional patterns in groundwater elevation data and groundwater flow across High Creek Fen.

5. Conclusion

Although the data presented do not definitively describe the groundwater sources to High Creek Fen, the data fill in gaps in our understanding of groundwater hydrologic dynamics. A multi-year study in which groundwater elevation, hydraulic head and stream discharge were continually measured, thereby improving the statistical power of the data set, could reveal more conclusive patterns in groundwater hydrology. In addition, other lines of evidence such as water chemistry and stable isotopes could help clarify the importance of trends identified in the presented hydrologic data; these results are presented in the next chapter.

CHAPTER 3: The Hydrochemistry of High Creek Fen

1. Introduction

Fens are nutrient-rich wetland ecosystems often located in northern-latitude and high-altitude regions of North America. The South Park basin, located approximately 3000 m above sea level (asl) in central Colorado, features at least 31 rich and extremely rich fens, a distinction attributed to fens with a high pH and high calcium and magnesium concentrations (Cooper 1996; Figure 1). High Creek Fen is the most southern extremely rich fen in North America. The unique groundwater chemistry at High Creek Fen has been attributed to the calcareous, glacially-derived sediments underlying the fen (Cooper 1996). Also, High Creek Fen is groundwater-fed, and groundwater is generally enriched in minerals as compared with surface waters from the same region due to greater contact with minerals in aquifer pores (Mazor 1991).

The first published study of the hydrochemistry of High Creek Fen identified three groundwater sources based on the chemical composition of surface water samples (Cooper 1996; Table 4; Figure 15). In addition, three other research studies, conducted in 1995, 1996 and 1997, investigated the hydrochemistry of High Creek Fen (Brand and Carpenter 1999). These four studies produced contrasting conclusions, probably because they had different foci and did not follow consistent field sampling or analytical protocol. Additionally, although the data were collected within a three-year period, there are many inconsistencies between the afore-mentioned studies.

As discussed in the previous chapter, the primary hypothesis of this work is that High Creek Fen is fed by a single, shallow groundwater source. If High Creek Fen is fed by a single groundwater source, the chemical signatures of groundwater samples collected throughout the fen should be very similar, and should vary together across seasonal gradients. Thus, the goal of this chapter is to investigate the sources of water to High Creek Fen using hydrochemical data, including stable isotopes of water and anion concentrations, collected during May 2007 to May 2008. In addition, this chapter includes a comparison of the hydrochemical data collected in this study with findings from the four previous studies in order to develop a better understanding of the spatial and temporal variability in groundwater and groundwater sources at High Creek Fen.

Table 4. From Cooper 1996. ‘Chemical characteristics of the three main water sources at High Creek Fen’.

Source	*n*	pH	K (µS cm^{-1})	Ca^{2+} (mg kg^{-1})	Mg^{2+} (mg kg^{-1})	Na^{+} (mg kg^{-1})	K^{+} (mg kg^{-1})	HCO_3^{-} (mg kg^{-1})	SO_4^{2-} (mg kg^{-1})	Cl^{-} (mg kg^{-1})
A	3	7.84	437	55.1	29.7	8.4	1.6	252.7	34.7	4.6
B	2	7.84	689	92.8	78.4	9.9	0.8	383.5	89.1	14.1
C	2	8.13	1613	67.2	97.7	25.4	2.7	247.6	815.4	42.6

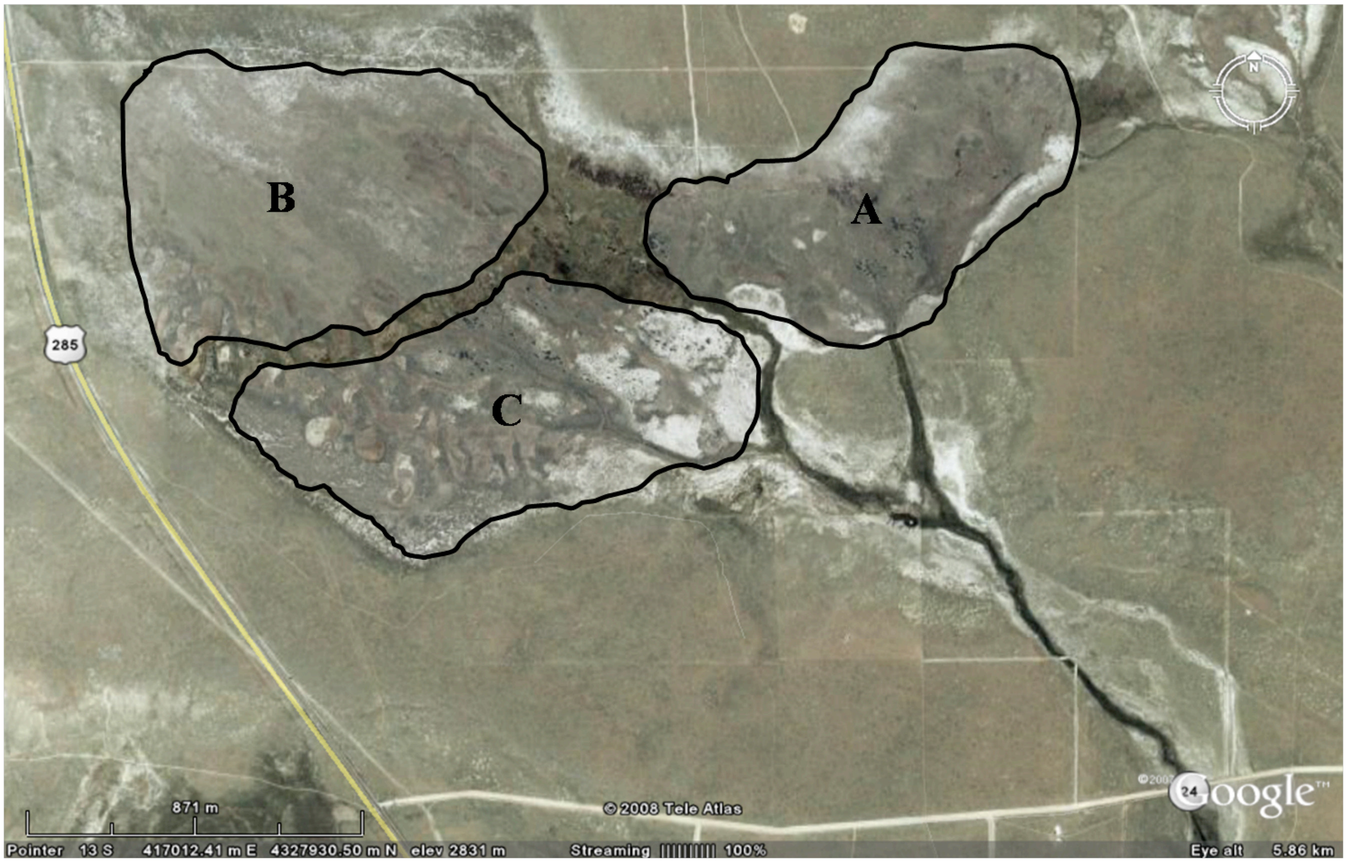


Figure 15. The locations of groundwater sources A, B and C at High Creek Fen, as described in Cooper 1996.

2. Materials and Methods

Groundwater and surface water temperature, conductivity and salinity were measured in the field using the YSI® Model 30 SCT Meter prior to collecting water samples. Groundwater samples from High Creek Fen (*n* = 42) (Figure 2) and Warm Springs Fen (*n* = 4), and surface water samples from High Creek (*n* = 7) and Fourmile Creek (*n* = 1) were collected between May 25, 2007 and May 28, 2008. All water samples collected over the study period were analyzed for δ^{18}oxygen ($\delta^{18}O$), a stable isotope of water; chloride (Cl^-); nitrate (NO_3^-); and sulfate (SO_4^{2}). Water samples collected between May 3, 2008 and May 29, 2008 were also analyzed for δdeuterium (δD), another stable isotope of water. At High Creek Fen, groundwater samples were collected from six piezometer nests (Figure 3). To collect groundwater samples at Nests 1-5, groundwater was hand-pumped from piezometer C, screened at 1.2 m below ground surface (bgs). Groundwater samples from Nest 6 were pumped from piezometer B, screened at 0.9 m bgs, the deepest piezometer at that location. Water samples were preserved in glass vials and refrigerated until analysis.

Water samples were submitted to the INSTAAR Stable Isotope Laboratory (SIL) for isotopic analysis, specifically for the stable isotopes δD and $\delta^{18}O$. Samples collected in 2007 were only analyzed for $\delta^{18}O$ whereas samples collected in 2008 were analyzed for $\delta^{18}O$ and δD. $\delta^{18}O$ and δD values were calculated using the equation (2),

$$\partial^{18}\mathrm{O} = \frac{(^{18}\mathrm{O}/^{16}\mathrm{O})\mathrm{sample} - (^{18}\mathrm{O}/^{16}\mathrm{O})\mathrm{standard}}{(^{18}\mathrm{O}/^{16}\mathrm{O})\mathrm{standard}} \times 1000 \tag{2}$$

where Standard Mean Ocean Water (SMOW) is the standard.

Water samples were analyzed for concentrations of Cl^-, NO_3^- and SO_4^{2-} using the Dionex Ion Chromatography System-2000 (http://www.dionex.com/en-us/ic/ICS2/lp39034.html). Linear regression analysis, Pearson's correlation coefficients using a two-tailed test of significance and descriptive statistics of $\delta^{18}O$, δD, Cl^-, NO_3^- and SO_4^{2-} data, such as mean, median, range, standard deviation and, was completed using the Descriptive Statistics module in OriginPro 8 (OriginLab Corporation 2008).

3. Results

3.1 $\delta^{18}O$ and δD values

The $\delta^{18}O$ and δD composition of groundwater within High Creek Fen and surface water in High Creek varied over the study period (Figures 16, 17 and 18). In general, the range of groundwater $\delta^{18}O$ and δD values was greater than of surface water $\delta^{18}O$ and δD values collected from High Creek (Table 5). The standard deviation of the $\delta^{18}O$ groundwater data (n=38) was 0.62‰ over the entire sampling period (May 25, 2007 to May 28, 2008) and the range was 4.35‰ whereas the standard deviation surface water data (n=10) was 0.83‰ and the range was 2.7‰. Groundwater in the northwest (Nest 1; Figure 3) and northeast (Nest 5; Figure 3) of High Creek Fen had the greatest $\delta^{18}O$ range of any of the groundwater sampling locations, 2.8‰ and 2.3‰ respectively (Table 6). δD values varied more than $\delta^{18}O$ for the sampling period from May 3, 2008 to May 28, 2008. The standard deviation of δD values in groundwater samples (n=22) was 5.7‰ as compared to 0.72‰ for $\delta^{18}O$ during the same period (Table 5). The range in δD was 34.71‰, which is approximately eight times greater than the $\delta^{18}O$ data range during the same period. Groundwater and surface water was relatively enriched in $\delta^{18}O$ and δD proceeding the snowmelt season, in June 2007 (Figures 16, 17 and 18). In 2008 groundwater and surface water was the most depleted in the $\delta^{18}O$ and δD during the snowmelt season, with the lowest sampled values occurring on May 3, 2008.

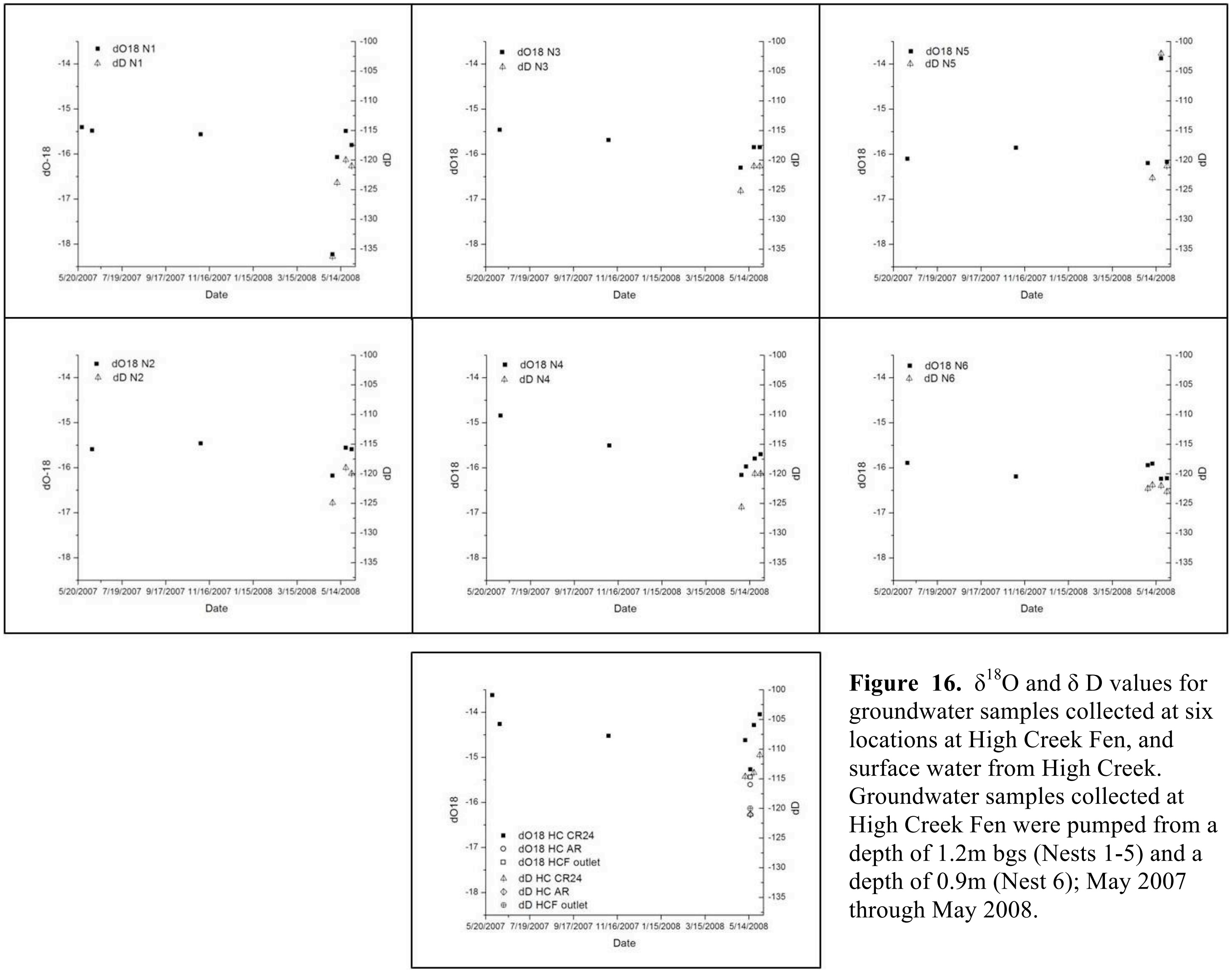


Figure 16. $\delta^{18}O$ and δ D values for groundwater samples collected at six locations at High Creek Fen, and surface water from High Creek. Groundwater samples collected at High Creek Fen were pumped from a depth of 1.2m bgs (Nests 1-5) and a depth of 0.9m (Nest 6); May 2007 through May 2008.

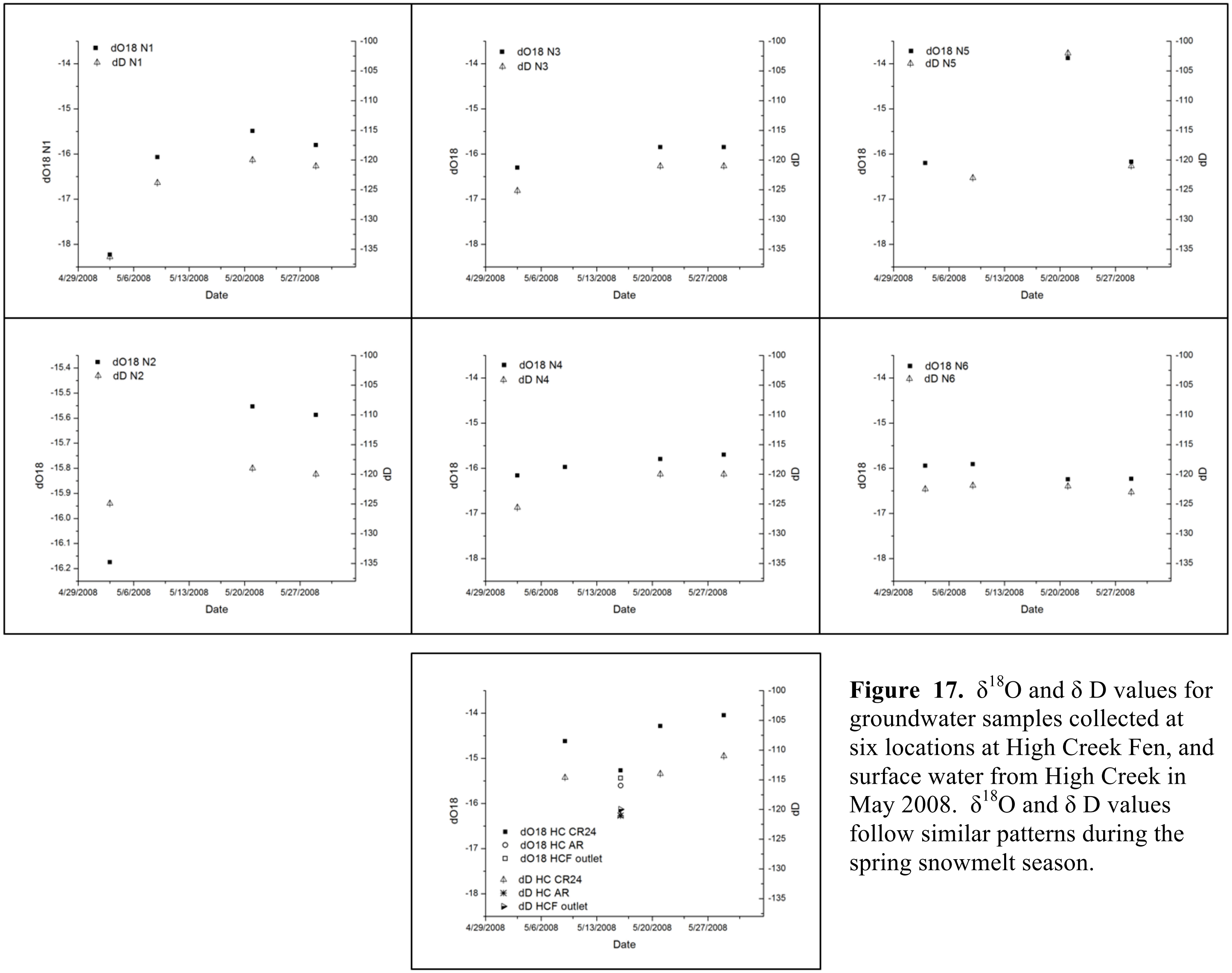


Figure 17. $\delta^{18}O$ and δ D values for groundwater samples collected at six locations at High Creek Fen, and surface water from High Creek in May 2008. $\delta^{18}O$ and δ D values follow similar patterns during the spring snowmelt season.

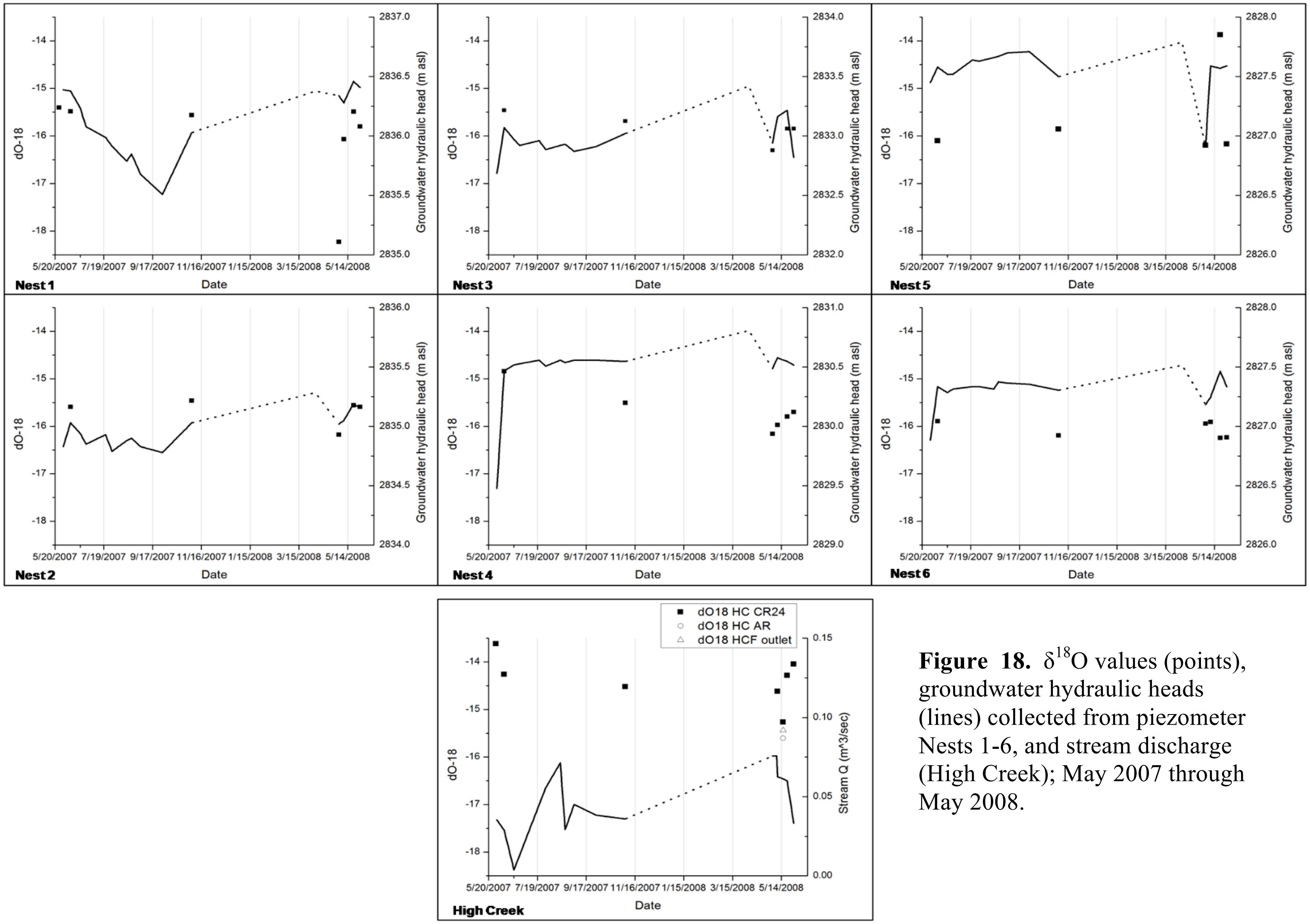


Figure 18. $\delta^{18}O$ values (points), groundwater hydraulic heads (lines) collected from piezometer Nests 1-6, and stream discharge (High Creek); May 2007 through May 2008.

Table 5. Descriptive statistics for $\delta^{18}O$ and δD values measured in groundwater samples collected at High Creek Fen, and surface water samples collected at High Creek.

		Groundwater				Surface Water			
Isotope	**Sample Period**	***n***	**Mean (‰)**	**Std. Dev. (‰)**	**Range (‰)**	***n***	**Mean (‰)**	**Std. Dev. (‰)**	**Range (‰)**
$\delta^{18}O$	May 25,2007 - May 28,2008	38	-15.8	0.62	4.35	10	-14.8	0.83	2.7
$\delta^{18}O$	May 3,2007 - May 28,2008	22	-15.93	0.72	4.36	6	-14.87	0.65	1.56
δD	May 3,2007 - May 28,2008	22	-121.65	5.7	34.7	6	-117.05	4.23	9.9

Table 6. Descriptive statistics for $\delta^{18}O$ values measured in groundwater samples collected from piezometer nests within High Creek Fen, and surface water samples collected at High Creek between May 2007 and May 2008. The units for $\delta^{18}O$ values are parts per thousand (‰).

Sample	N	Mean	Min	Max	Standard Deviation	Range
HCF Nest 1	7	-16.00	-18.2268	-15.4	1.00784	2.8268
HCF Nest 2	5	-15.67	-16.1742	-15.4562	0.28587	0.71801
HCF Nest 3	5	-15.83	-16.2982	-15.46	0.30692	0.83819
HCF Nest 4	6	-15.66	-16.1606	-14.84	0.46099	1.32055
HCF Nest 5	5	-15.64	-16.1953	-13.8706	0.99706	2.32469
HCF Nest 6	6	-16.07	-16.2425	-15.89	0.16932	0.35245
High Creek CR24	7	-14.37	-15.2652	-13.62	0.51181	1.64515

A correlation analysis of the $\delta^{18}O$ and δD data identified a significant relationship between $\delta^{18}O$ and δD values, as well as significant relationships between $\delta^{18}O$ values in groundwater collected from different locations at High Creek Fen (Tables 7 and 8). Pearson correlation coefficient results from a two-tailed test of significance showed that $\delta^{18}O$ and δD values were highly correlated (R^2=0.91, p=5e^{-12}) in groundwater samples collected from May 3, 2008 to May 29, 2008. In addition, a two-tailed test of significance identified significant ($p \leq 0.05$) relationships between groundwater $\delta^{18}O$ values at Nests 1 and 2, Nests 1 and 3, and Nests 3 and 4 (Tables 7 and 8). Also, two different correlation analyses were performed on the $\delta^{18}O$ data in order to investigate if there were any differences in the stable isotope signatures of groundwater between the entire study period and just the snowmelt period (May 3, 2008 to May 29, 2008 (Tables 7 and 8).

The equation of the local meteoric water line (LMWL) for groundwater in High Creek Fen, $\delta D = 7.6\delta^{18}O\text{-}0.8$, has a steeper slope than for surface water in High Creek, $\delta D = 6.4\delta^{18}O\text{-}21.3$ (Figure 19). The LMWL for groundwater at High Creek fen has a similar slope to the global meteoric water line, $\delta D = 8^{18}O + 10$ (Craig 1961), but has a smaller y-intercept and thus is more depleted in δD (Figure 19). The LMWL equations, identified through a simple linear regression analysis, explain more than 90% of the variation in the data (Figure 19). The groundwater data has a higher overall variance than surface water however this trend may be reversed with the elimination of two outliers in the groundwater data set.

Table 7. Pearson correlation coefficients (R^2) and significance values (in parentheses) for $\delta^{18}O$ values in groundwater and surface water collected at High Creek Fen and High Creek between May 2007 and May 2008.

Pearson Correlations	dO-18 N1	dO-18 N2	dO-18 N3	dO-18 N4	dO-18 N5	dO-18 N6	dO-18 HC CR24
dO-18 N1	1	0.96 (0.003)	0.78 (0.05)	0.4 (0.18)	0.1 (0.58)	0.17 (0.4)	0.12 (0.33)
dO-18 N2		1	0.7 (0.08)	0.36 (0.28)	0.1 (0.6)	0.32 (0.32)	0.77 (0.12)
dO-18 N3			1	0.88 (0.02)	0.001 (0.96)	$4e^{-4}$ (0.97)	0.09 (0.7)
dO-18 N4				1	0.03 (0.77)	0.01 (0.83)	0.07 (0.66)
dO-18 N5					1	0.27 (0.37)	0.2 (0.85)
dO-18 N6						1	0.17 (0.49)
dO-18 HC CR24							1

Table 8. Pearson correlation coefficients (R^2) and significance values (in parentheses) for $\delta^{18}O$ data from groundwater collected between May 3, 2008 and May 29, 2008 at High Creek Fen.

Pearson Correlations	$\delta^{18}O$ N1	$\delta^{18}O$ N2	$\delta^{18}O$ N3	$\delta^{18}O$ N4	$\delta^{18}O$ N5	$\delta^{18}O$ N6
$\delta^{18}O$ N1	1	0.94 (0.16)	0.68 (0.38)	0.64 (0.2)	0.23 (0.5)	0.4 (0.36)
$\delta^{18}O$ N2		1	0.88 (0.22)	0.93 (0.17)	0.2 (0.7)	0.14 (0.75)
$\delta^{18}O$ N3			1	0.99 (0.04)	0.01 (0.9)	0.001 (0.98)
$\delta^{18}O$ N4				1	0.04 (0.8)	0.003 (0.94)
$\delta^{18}O$ N5					1	0.36 (0.4)
$\delta^{18}O$ N6						1

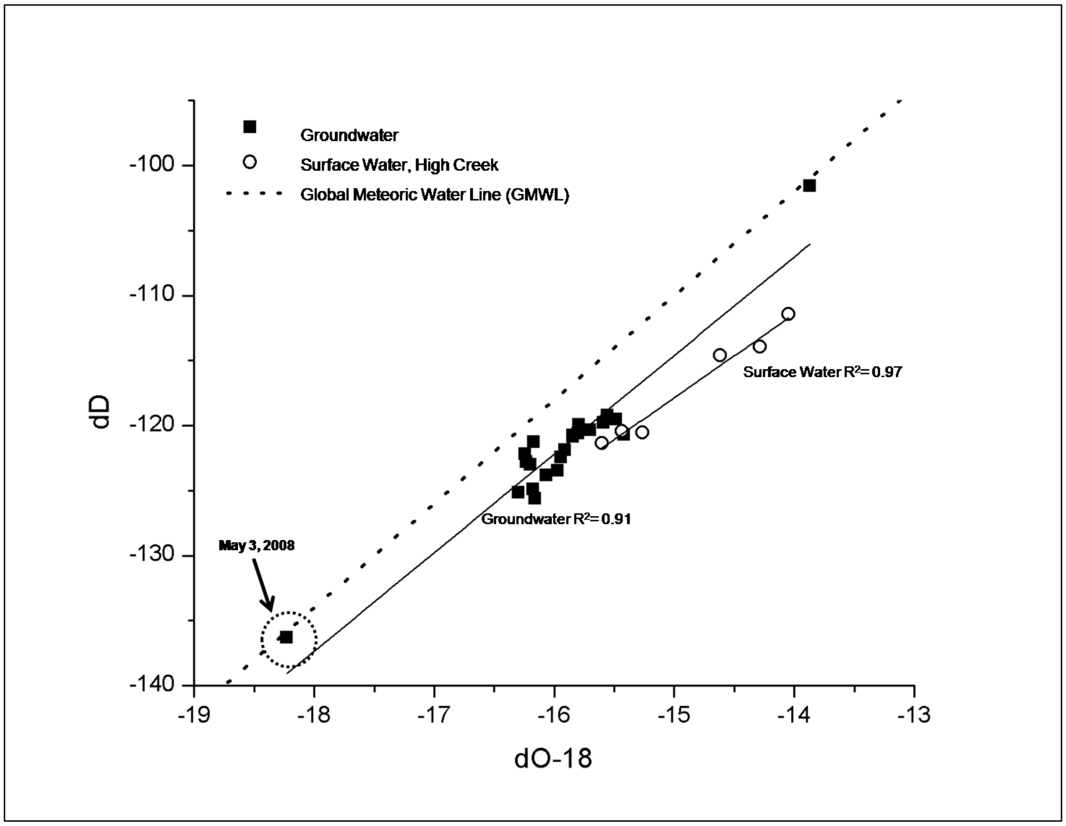


Figure 19. Plot of $\delta^{18}O$ versus δD from groundwater and surface water samples collected at High Creek Fen and High Creek, respectively. The equation of the local meteoric water line (LMWL) for groundwater samples is $\delta D = 7.6\delta^{18}O-0.8$. For surface water samples the LMWL equation is $\delta D = 6.4\delta^{18}O-21.3$. The equation for the global meteoric water line is $\delta D = 8^{18}O + 10$ (Craig 1961). In general, the groundwater samples collected at High Creek Fen fall within a narrow range of $\delta^{18}O$ and δD values. The two exceptions were collected from piezometer nests 1 and 5. The sample that was the most depleted in $\delta^{18}O$ and δD was collected from nest 1 during the snowmelt period on May 3, 2008. The sample that was the most enriched in $\delta^{18}O$ and δD was collected on May 21, 2008 from nest 5, the piezometer nest located in the northeast area of High Creek Fen.

3.2 Groundwater and surface water anion concentrations: chloride, nitrate and sulfate

3.2.1 Chloride Data

The chloride concentration in groundwater at High Creek and surface water at High Creek was dynamic throughout the sample collection period, July 2007 to May 2008. In the northwest and northeast regions of High Creek Fen (piezometer Nests 1 and 5, respectively) chloride concentrations demonstrate seasonal variations increase from summer and fall (Figure 20). In these locations, chloride concentrations increase from summer to fall whereas concentrations decrease over the course of the spring season. In the northwest chloride concentrations appear to have an inverse relationship with groundwater hydraulic head (Figure 21). Chloride concentrations in the other groundwater sampling locations throughout High Creek Fen generally follow a different seasonal pattern. Chloride concentrations collected from groundwater in the central region of High Creek Fen (Figure 3; piezometer Nests 2, 3, 4 and 5) increase from summer to fall and increase again during the spring snowmelt season. Chloride concentrations in surface water samples collected at High Creek do not show a distinct seasonal pattern.

Mean chloride concentrations were consistent across groundwater sampling locations and High Creek, with the exception of groundwater collected at piezomter Nest 3 (Figure 3; Table 9). With the exclusion of Nest 3 data, mean chloride concentrations of groundwater at all locations and surface water ranged from two to four parts per million. Groundwater collected at Nest 3 had the highest mean chloride concentration and greatest data range across the study period. The chloride concentration data ranges were greater for groundwater sampled in the northern area of High Creek Fen (piezometer Nests 1, 3, and 5) than in the southern area (Nests 2, 4 and 6; Table 9).

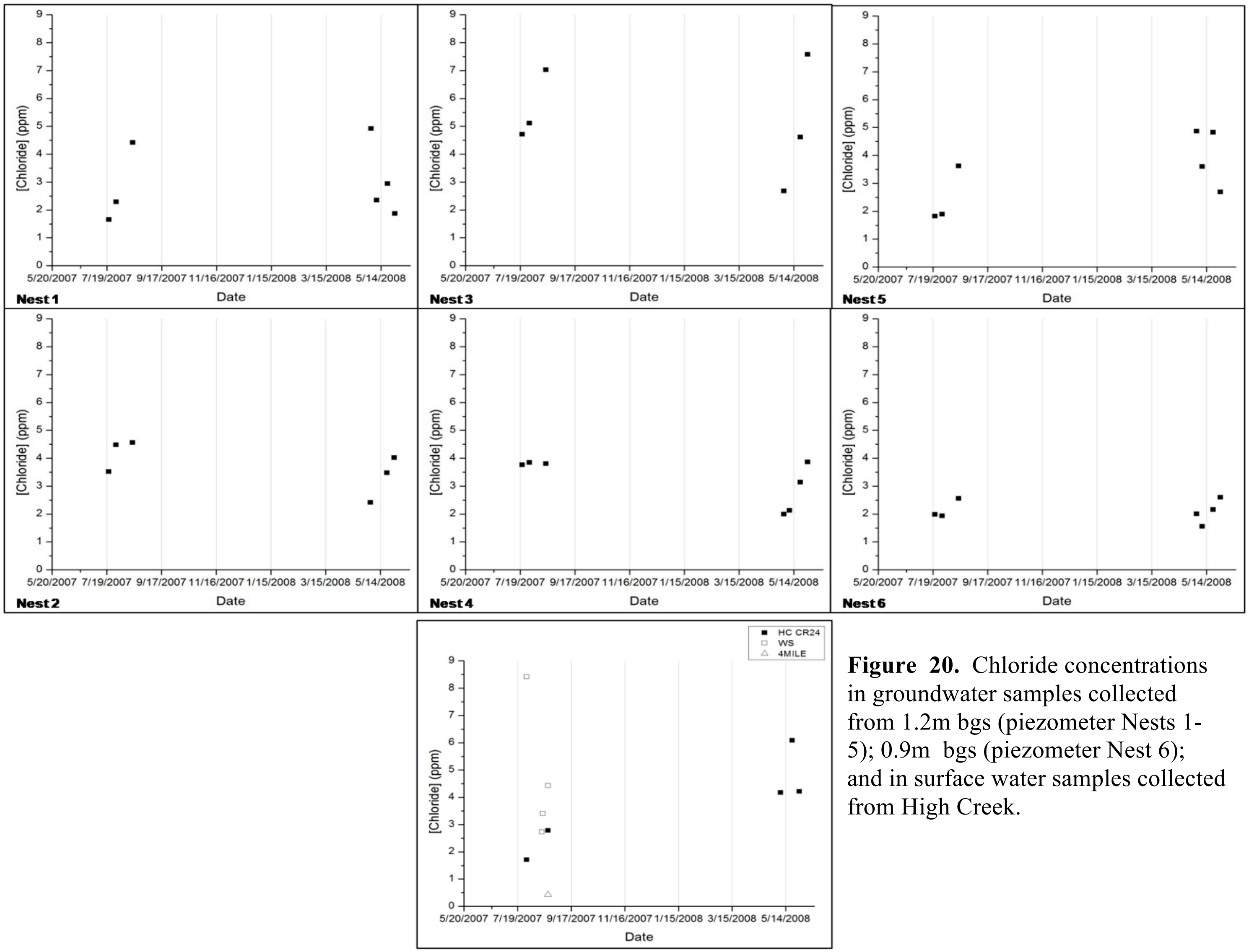


Figure 20. Chloride concentrations in groundwater samples collected from 1.2m bgs (piezometer Nests 1-5); 0.9m bgs (piezometer Nest 6); and in surface water samples collected from High Creek.

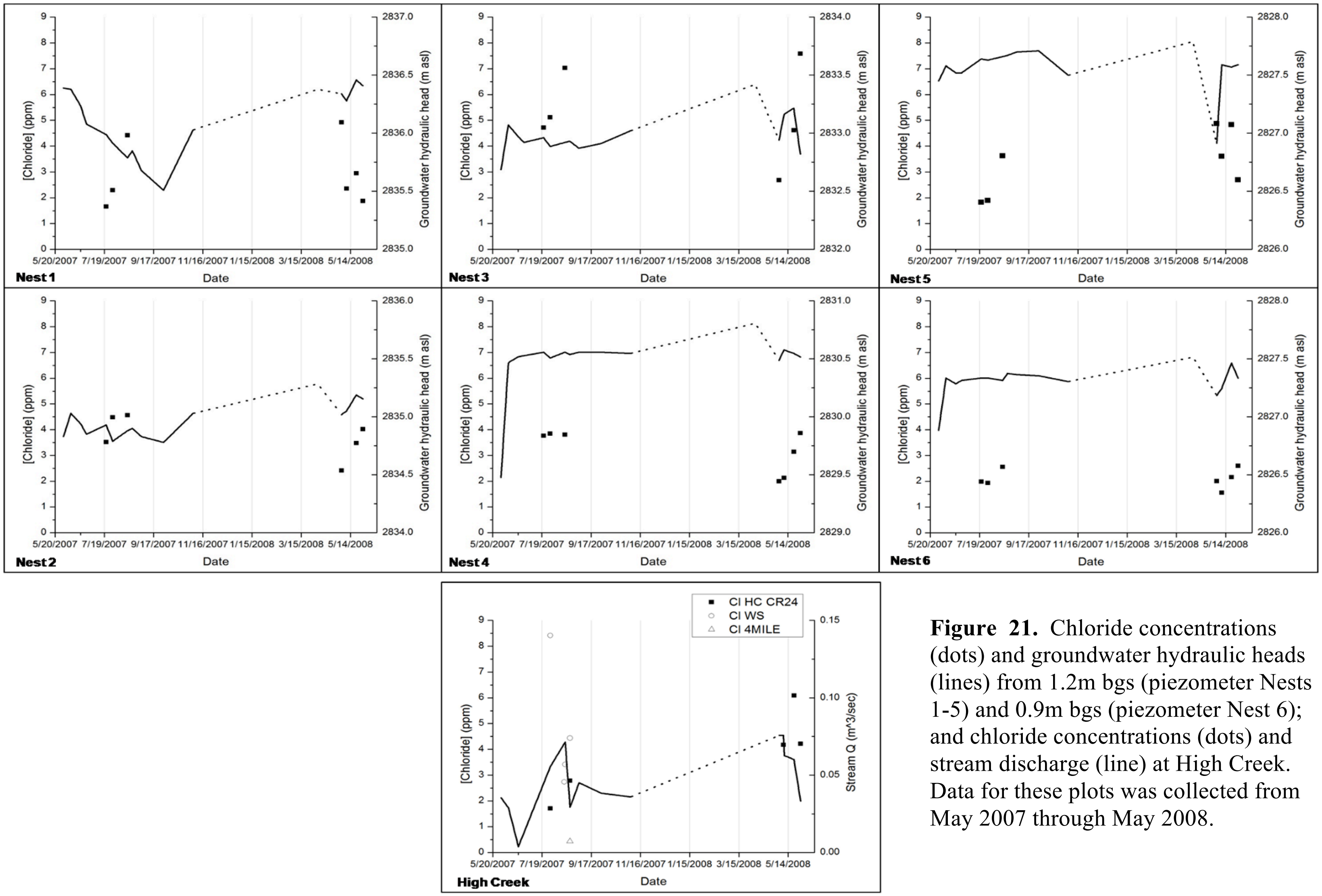


Figure 21. Chloride concentrations (dots) and groundwater hydraulic heads (lines) from 1.2m bgs (piezometer Nests 1-5) and 0.9m bgs (piezometer Nest 6); and chloride concentrations (dots) and stream discharge (line) at High Creek. Data for these plots was collected from May 2007 through May 2008.

Table 9. Descriptive statistics for chloride concentrations in samples collected between July 2007 – May 2008. Chloride concentration values are reported in units of parts per million (ppm).

[Chloride]	N1	N2	N3	N4	N5	N6	HC CR24
n	7	6	6	7	7	7	5
mean	2.92	3.75	5.29	3.22	3.33	2.11	3.80
std. dev.	1.27	0.80	1.78	0.83	1.26	0.37	1.65
range	3.27	2.15	4.90	1.87	3.04	1.04	4.38
min	1.65	2.42	2.68	2.00	1.83	1.55	1.71
max	4.92	4.56	7.58	3.87	4.87	2.60	6.09

Pearson correlation coefficient results from a two-tailed test of significance showed that chloride concentrations in groundwater collected within the central and southern areas of High Creek Fen were significantly correlated ($p \leq 0.05$; Table 10). This result is consistent with the time series results presented in Figures 20 and 21. Between July 21 and November 4, 2007 chloride concentrations measured in groundwater in the northern region of High Creek Fen (piezometer Nests 1 and 5, and Nests 3 and 5) are highly correlated, as are chloride concentrations in groundwater samples collected in the southern area of the fen (piezometer Nests 2 and 4; Table 11). Between May 3 and May 28, 2008 different significant relationships occurred between groundwater sources. Groundwater collected in the western area of High Creek Fen had significantly correlated chloride concentrations, as did groundwater collected in the southern area of High Creek Fen (Table 12).

Table 10. Pearson correlation coefficients, calculated from a two-tailed significance test, of chloride concentration data. The data presented is from water samples collected throughout the study period, from July 21, 2007 to May 28, 2008.

Pearson Correlations	ClN1	ClN2	ClN3	ClN4	ClN5	ClN6	ClHC CR24
ClN1	1	0.12 (0.5)	0.12 (0.5)	0.18 (0.3)	0.5 (0.07)	0.03 (0.68)	0.28 (0.64)
ClN2		1	0.80 (0.05)	0.89 (0.02)	0.32 (0.24)	0.2 (0.38)	0.98 (0.08)
ClN3			1	0.80 (0.05)	0.16 (0.44)	0.89 (0.04)	0.005 (0.95)
ClN4				1	0.46 (0.1)	0.38 (0.14)	0.64 (0.4)
ClN5					1	$1e^{-4}$ (0.98)	0.88 (0.2)
ClN6						1	0.17 (0.73)
ClHC CR24							1

Table 11. Correlation coefficients for chloride concentration data, analyzed from water samples collected between July 21, 2007 and November 4, 2007.

Correlation Coefficients: May - November 2007	**N1**	**N2**	**N3**	**N4**	**N5**	**N6**
N1	1	0.05 (0.71)	0.97 (0.002)	0.03 (0.79)	0.92 (0.009)	0.68 (0.09)
N2		1	0.02 (0.81)	0.87 (0.02)	$2e^{-4}$ (0.98)	0.38 (0.27)
N3			1	0.02 (0.8)	0.93 (0.007)	0.67 (0.09)
N4				1	$2e^{-3}$ (0.94)	0.40 (0.25)
N5					1	0.53 (0.16)
N6						1

Table 12. Correlation coefficients for chloride concentration data, analyzed from water samples collected between May 3, 2008 and May 29, 2008.

Correlation Coefficients: May 3- May 29 2008	**N1**	**N2**	**N3**	**N4**	**N5**	**N6**	**HC CR24**
N1	1	0.9997 (0.01)	0.92 (0.19)	0.998 (0.03)	0.61 (0.43)	0.82 (0.28)	0.89 (0.22)
N2		1	0.93 (0.18)	0.9995 (0.015)	0.63 (0.42)	0.83 (0.27)	0.9 (0.21)
N3			1	0.938 (0.16)	0.86 (0.24)	0.98 (0.096)	0.9975 (0.03)
N4				1	0.65 (0.4)	0.85 (0.26)	0.91 (0.2)
N5					1	0.95 (0.15)	0.89 (0.21)
N6						1	0.99 (0.06)
HC CR24							1

3.2.2 Nitrate Data

Nitrate concentrations in groundwater were relatively consistent, as compared to chloride concentrations, across sampling locations within High Creek Fen. In July 2007 nitrate concentrations in groundwater and surface water from High Creek, Warm Springs Fen and Fourmile Creek ranged between 0.5 and 1.5 parts per million (ppm) at all locations (Figure 22). There was a greater range in groundwater nitrate concentrations later in the summer (Figure 22; Table 13). In august, nitrate concentrations were the highest in groundwater collected from the western area of High Creek Fen (Figure 3; piezometer Nests 1 and 2), and the lowest in groundwater collected from the most southern groundwater sampling location (piezometer Nest 4). Nitrate concentrations were higher during the May 3, 2008 to May 28, 2008 sampling period as compared to groundwater and surface water collected in summer and fall 2007. In general nitrate concentrations in groundwater collected during May 2008, the snowmelt season, ranged between 1 and 2.5 ppm. Groundwater collected from the southeast area of High Creek Fen on May 3, 2008 was an outlier in the data set; the nitrate concentration in this sample was 8.5 ppm.

Results from a two-tailed test of significance indicate that groundwater nitrate concentrations were significantly correlated between locations within High Creek Fen, and were correlated with groundwater hydrologic dynamics. There were significant correlations between groundwater nitrate concentrations collected in the north-central and northeast area of High Creek Fen (Nests 3 and 5; Table 14), and in the east area of the fen (Nests 5 and 6; Table 14). Pearson correlation coefficient results suggest that nitrate concentrations are significantly correlated to groundwater hydraulic head at various locations throughout High Creek Fen and stream discharge (Table 15).

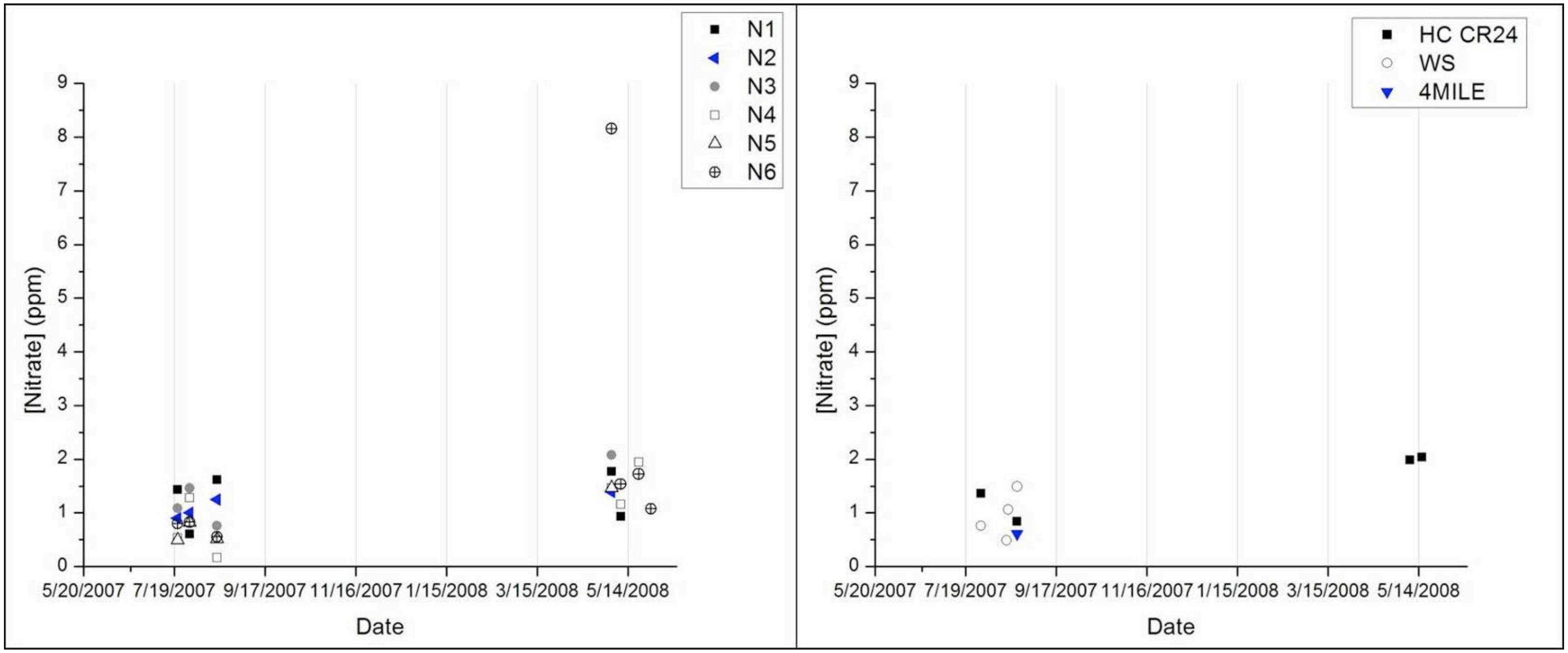


Figure 22. Nitrate concentration data from groundwater collected at High Creek Fen and Warm Springs Fen, and surface water collected at High Creek and Fourmile Creek.

Table 13. Descriptive statistics of nitrate concentration data, July 2007- May 2008. Nitrate concentrations are reported in units of parts per million (ppm).

[Nitrate]	N1	N2	N3	N4	N5	N6	HC CR24
n	5	4	4	6	4	7	4
mean	1.27	1.13	1.35	1.09	0.82	2.10	1.55
std. dev.	0.49	0.23	0.57	0.65	0.45	2.71	0.57
range	1.17	0.49	1.32	1.79	0.97	7.60	1.20
min	0.60	0.90	0.76	0.16	0.49	0.55	0.84
max	1.77	1.39	2.08	1.95	1.46	8.16	2.03

Table 14. Pearson's correlation coefficients for significant correlations between nitrate concentrations in groundwater collected from sampling locations at High Creek Fen throughout the entire study period.

Pearson Correlations: Nitrate	N1	N2	N3	N4	N5	N6
N1	1	0.4 (0.37)	0.004 (0.94)	0.12 (0.57)	0.06 (0.76)	0.28 (0.36)
N2		1	0.19 (0.56)	0.06 (0.76)	0.47 (0.32)	0.55 (0.26)
N3			1	0.89 (0.06)	0.91 (0.04)	0.77 (0.12)
N4				1	0.72 (0.15)	0.17 (0.42)
N5					1	0.90 (0.05)
N6						1

Table 15. Pearson's correlation coefficients for significant correlations between nitrate concentration at different locations, and groundwater level, precipitation and stream discharge at High Creek.

Pearson Correlations: Nitrate	N1 GW	N2 GW	N3 GW	N4 GW	N5 GW	N6 GW	Total Precipitation	Stream Q
N1	0.92 (0.19)	0.55 (0.26)	0.17 (0.6)	0.55 (0.26)	0.17 (0.58)	0.36 (0.4)	0.58 (0.13)	**0.99 (0.007)**
N2	0.4 (0.55)	0.14 (0.91)	0.05 (0.85)	0.3 (0.64)	0.99 (0.03)	0.05 (0.85)	0.16 (0.6)	0.97 (0.1)
N3	**0.99 (0.01)**	0.42 (0.55)	0.78 (0.31)	0.98 (0.1)	0.48 (0.51)	0.78 (0.31)	0.02 (0.87)	0.03 (0.89)
N4	**0.93 (0.03)**	**0.82 (0.04)**	0.7 (0.08)	0.74 (0.06)	0.46 (0.2)	**0.79 (0.04)**	0.02 (0.79)	0.14 (0.54)
N5	0.73 (0.35)	0.91 (0.19)	**0.99 (0.05)**	0.84 (0.26)	0.04 (0.87)	**0.99 (0.05)**	$4e^{-5}$ (0.99)	0.16 (0.74)
N6	0.75 (0.06)	**0.65 (0.05)**	0.55 (0.09)	0.63 (0.06)	**0.74 (0.03)**	**0.78 (0.02)**	0.04 (0.66)	0.26 (0.31)

3.2.3 Sulfate Data

Sulfate concentrations had the greatest range of the anions measured in groundwater and surface water samples collected from High Creek Fen and High Creek over the study period. The overall range in groundwater sulfate concentrations was approximately 170 ppm whereas the range in surface water concentrations was approximately 230 ppm (Figure 23). Groundwater samples collected at piezometer Nests 2, 4 and 6 had lower sulfate concentration ranges and the standard deviations than groundwater collected at Nests 1, 3 and 5 (Figure 3; Table 16). Between July and September 2007 groundwater collected in the northern and western area of High Creek Fen (piezometer Nests 1, 2 and 3; Figure 3) contained higher concentrations of sulfate than groundwater in the east and south (Nests 4, 5 and 6). Also, groundwater sulfate concentrations at piezometer Nests 1, 2 and 3 steadily decreased from July to September 2007 (Figure 24). In general, groundwater samples collected between May 3 and May 28, 2008 had lower sulfate concentrations than samples collected in 2007 (Figure 24). However groundwater samples collected in northwest and northeast areas of High Creek Fen on May 3, 2008 contained the highest sulfate concentrations measured across the entire study period (Figures 23 and 24). Sulfate concentrations in High Creek ranged between 135 and 230 ppm between May 3 and May 28, 2008. These high surface water sulfate concentrations occurred during the period when groundwater collected at Nests 1 and 5 contained the highest concentrations of sulfate (Figure 23).

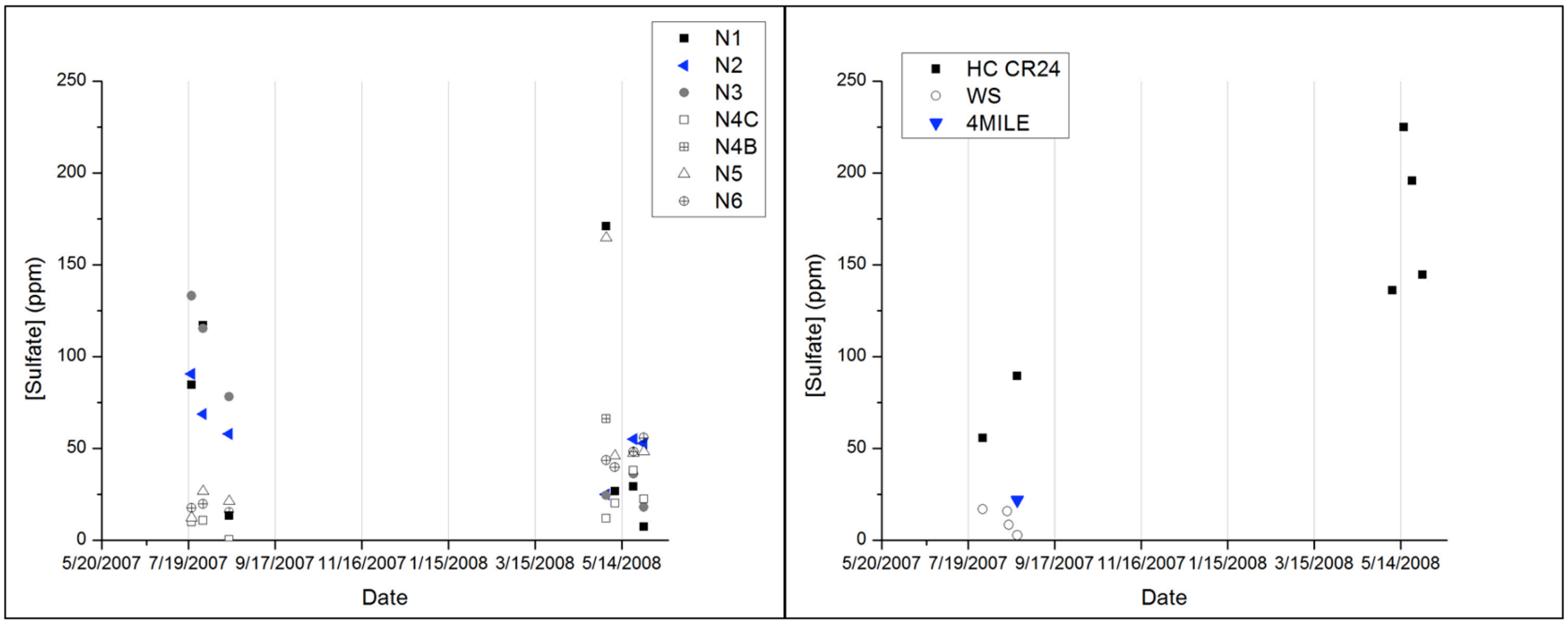


Figure 23. Sulfate concentration data from groundwater collected at High Creek Fen and Warm Springs Fen, and surface water collected at High Creek and Fourmile Creek between July 21, 2007 and May 28, 2008.

Table 16. Descriptive statistics of sulfate concentrations, measured in parts per million (ppm), from water samples collected between July 2007- May 2008 at High Creek Fen and High Creek.

[Sulfate]	N1	N2	N3	N4	N5	N6	HC CR24
n	7	6	6	8	7	7	6
mean	64.25	58.35	67.55	22.54	52.43	34.36	141.12
std. dev.	62.01	21.42	49.03	12.06	51.55	16.47	63.27
range	163.77	65.50	115.17	65.83	152.45	40.46	169.37
min	7.34	25.04	18.02	0.46	12.35	15.41	55.61
max	171.11	90.55	133.19	66.29	164.80	55.87	224.98

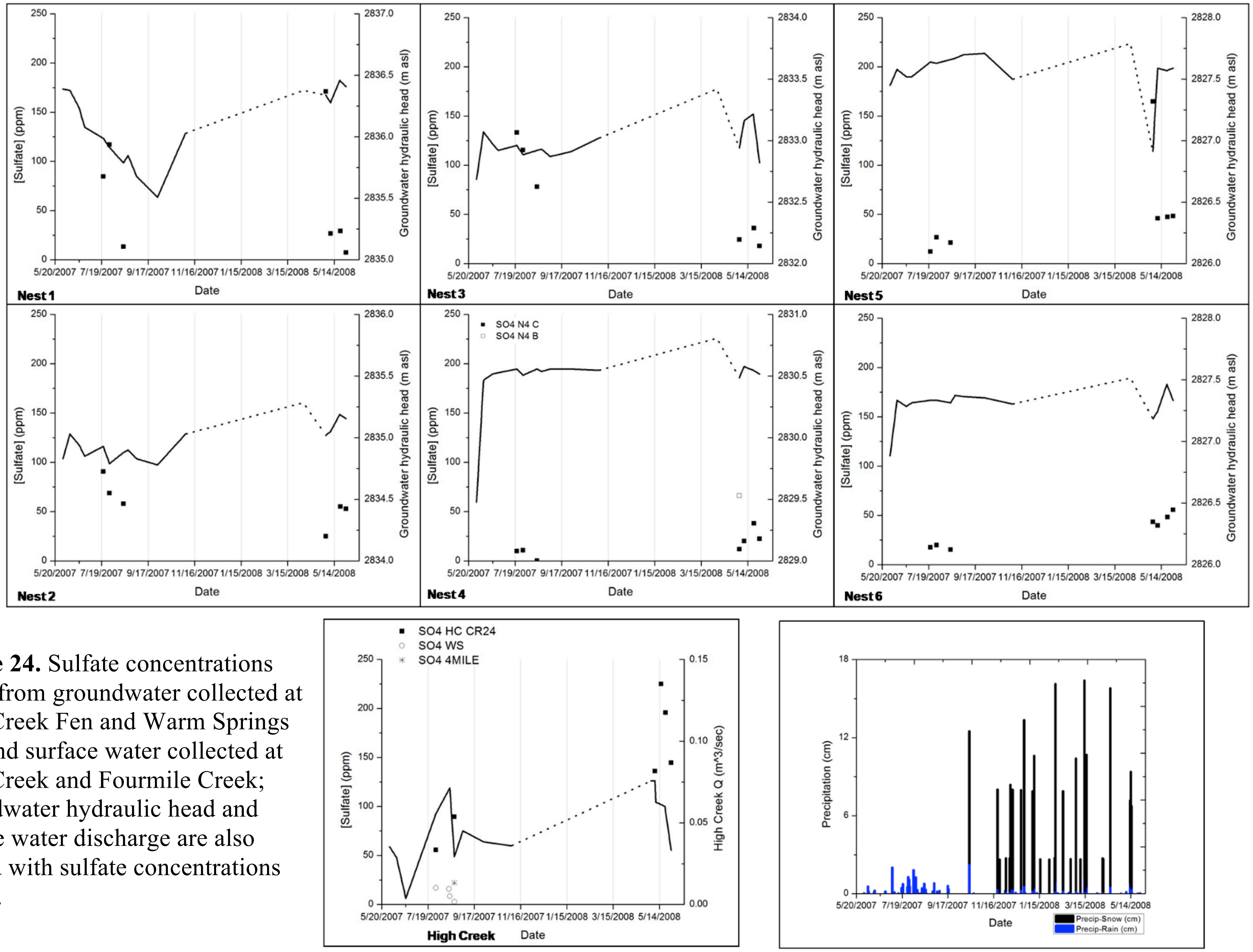


Figure 24. Sulfate concentrations (dots) from groundwater collected at High Creek Fen and Warm Springs Fen, and surface water collected at High Creek and Fourmile Creek; groundwater hydraulic head and surface water discharge are also plotted with sulfate concentrations (lines).

Pearson correlation coefficient results from a two-tailed test of significance showed that sulfate concentrations in groundwater collected at different locations within High Creek Fen were significantly correlated ($p \leq 0.05$; Table 17). Groundwater sulfate concentration at Nest 2, in the southwest area of High Creek Fen, was significantly correlated to groundwater sulfate concentration at Nest 3, located in the north-central area of the fen, and groundwater sulfate concentration at Nest 5, in the northeast area (Figure 3; Table 17). In addition, sulfate concentrations in groundwater at Nests 4 and 6, both located the southern area of High Creek Fen, were significantly correlated (Table 17).

Table 17. Correlation coefficients for sulfate concentration data, analyzed from water samples collected between July 2007 and May 2008.

[Sulfate]	N1	N2	N3	N4	N5	N6
N1	1	R^2=0.07, p=0.6	R^2=0.03, p=0.76	R^2=0.09, p=0.5	R^2=0.4, p=0.13	R^2=0.03, p=0.7
N2		1	R^2=0.7, p=0.04	R^2=0.02, p=0.77	R^2=0.75, p=0.02	R^2=0.37, p=0.2
N3			1	R^2=0.27, p=0.3	R^2=0.4, p=0.18	R^2=0.8, p=0.02
N4				1	R^2=3e^{-3}, p=0.9	R^2=0.58, p=0.05
N5					1	R^2=0.24, p=0.27
N6						1

4. Discussion

Previous research identified three groundwater sources at High Creek Fen (Cooper 1996; Table 4; Figure 15). Water chemistry data collected at High Creek Fen between May 25, 2007 and May 28, 2008 suggests that High Creek Fen is fed by two groundwater sources originating in the northwest and the northeast corners of the fen. These results are consistent with the findings presented in the previous chapter, Groundwater hydrology of High Creek Fen. In addition, water chemistry data supports the conclusion that the hydrology of High Creek Fen is spatially and temporally variable.

Fingerprint diagrams of anion data (Figures 25 and 26) and correlation coefficient results (Tables 7-8; 10-12; 14-15; 17) demonstrate that the chemical compositions of groundwater collected at the locations of sources A, B and C (Table 4; Figure 15) were not distinct during the study period. In fact, anion fingerprints did not cluster according to location. Groundwater collected from a majority of the sampling locations at High Creek Fen and at High Creek had similar anion concentration profiles (Figures 25 and 26), with the exception of groundwater collected from nest 6 (southeast; Figure 3). Hydrologic and chemical data indicates that groundwater in the southeast area of High Creek Fen is not as temporally variable as groundwater in other locations. Groundwater at nest 6 had a relatively low range of groundwater table levels, groundwater hydraulic heads, $\delta^{18}O$ values, chloride concentrations and sulfate concentrations compared to other locations during the study period. Groundwater at nest 6 is influenced by the hydrology and chemistry from all areas of High Creek Fen, and potentially Fourmile Creek (Chapter 2).

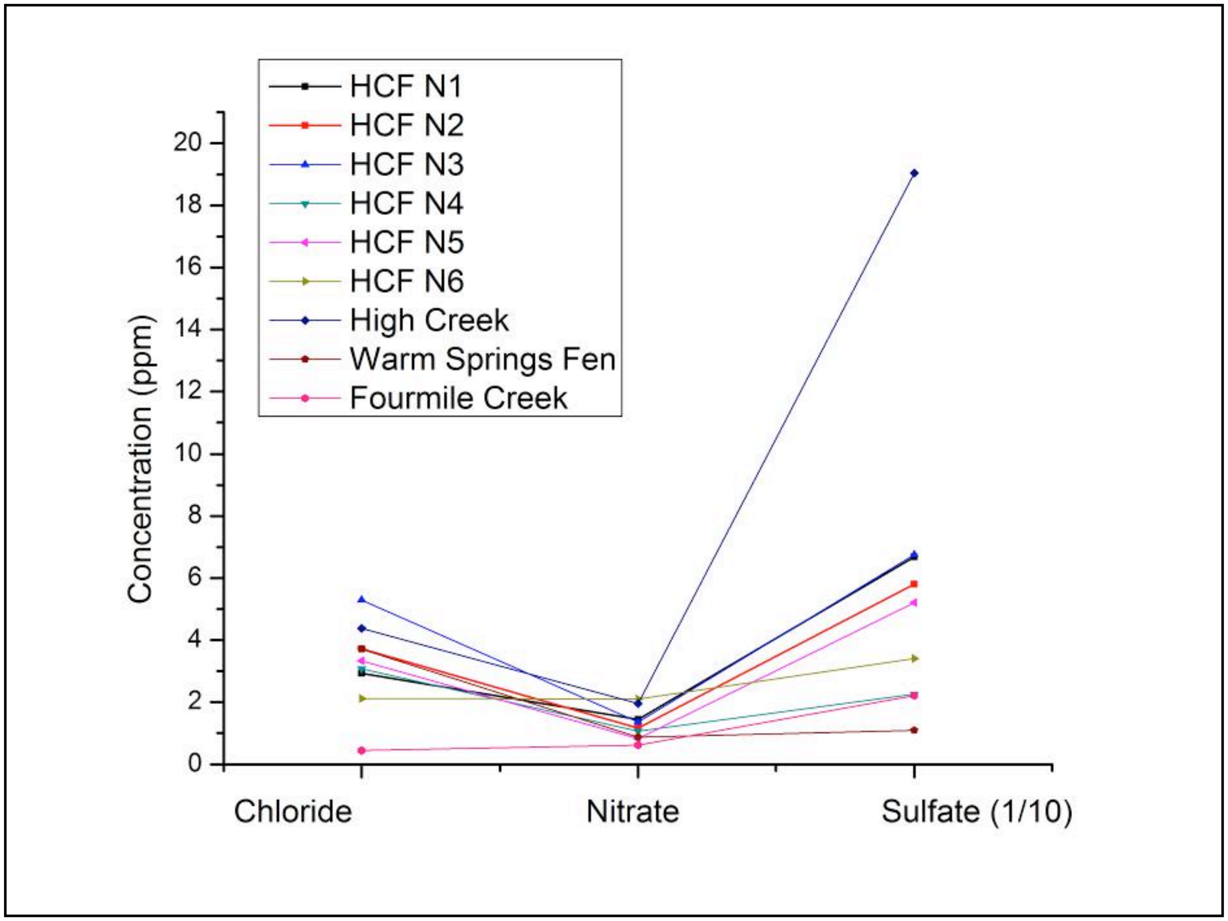


Figure 25. Fingerprint diagram of groundwater chemistry at High Creek Fen and Warm Springs Fen, and surface water at High Creek and Fourmile Creek. Plotted anion concentrations are mean values for each location.

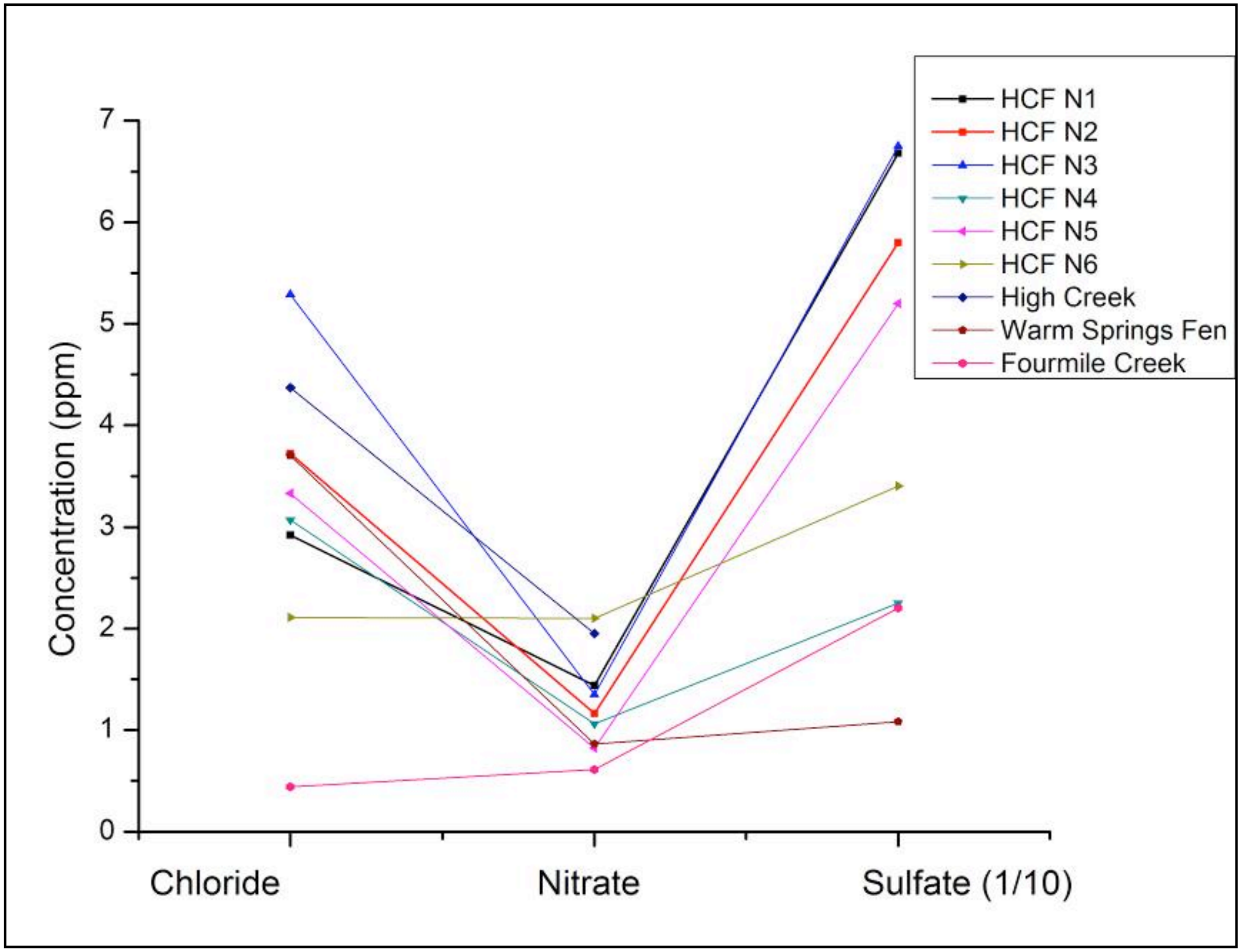


Figure 26. Fingerprint diagram of groundwater and surface water chemistry in the High Creek Fen watershed, excluding the High Creek mean sulfate concentration.

Correlation coefficient results identified locations within High Creek Fen that had consistently similar groundwater chemistry. Pairwise comparisons demonstrate that groundwater collected in the western area of High Creek Fen (nests 1, 2, 3 and 4) had significantly correlated $\delta^{18}O$ values and chloride concentrations (Tables 7-8; 10-12). Since $\delta^{18}O$ and chloride are conservative tracers for hydrologic systems (Schwartz and Zhang 2003), it is probable that there are subsurface connections between groundwater in this area of High Creek Fen. This finding is consistent with hydrologic evidence that the western area is fed by the primary groundwater source to the fen, which originates to the northwest of High Creek Fen.

Groundwater hydraulic head time series results from the previous chapter suggest that High Creek Fen is fed by two sources of groundwater; the primary source originates from the northwest of the fen (nest 1; Figure 3) whereas the other source probably originates from the northeast (nest 3; Figure 3). $\delta^{18}O$ and δD data indicate that groundwater in the northwest corner of High Creek Fen has a different stable isotope signature than groundwater in the northeast corner of the fen (Table 5). Groundwater in the northwest of High Creek Fen has a relatively depleted $\delta^{18}O$ and δD signature compared to groundwater in the northeast. Groundwater $\delta^{18}O$ and δD composition is much more variable during the snowmelt season at nests 1 and 5 than at other locations. It is likely that the observed variability reflected the different pulses of meltwater inputs to surface water and groundwater during the snowmelt season.

Groundwater in the northwest was the most depleted in $\delta^{18}O$ on May 3, 2008 (-18.23‰; Figure 19) whereas groundwater in the northeast was the most depleted in $\delta^{18}O$ on May 9, 2008 (-16.2‰). Groundwater in the northwest and northeast were the most enriched in $\delta^{18}O$ at the end of the snowmelt season, which occurred on approximately May 25 in 2007 and 2008. In addition, the stable isotope composition of groundwater collected from nest 1 on May 3, 2008 and from nest 5 on May 21, 2008 was consistent with the global meteoric water line (GMWL), whereas the composition of all other collected samples was relatively enriched in δ^{18}O compared to the GMWL (Figure 19).

According to Craig (1961), waters that fall below the GMWL are usually from closed basins or other environments in which evaporation regulates the δD/ δ^{18}O composition (Craig 1961). Therefore, it is possible that shallow groundwater at a majority of the locations and times of year at High Creek Fen is influenced by evaporative processes, especially given that evaporative losses from the fen can be 3.25 times greater than precipitation (Table 1). Surface water is more depleted in δD and δ^{18}O compared to groundwater from High Creek Fen and the GMWL. The difference in δD/ δ^{18}O composition of groundwater and surface water compared to the GMWL is consistent with other studies of lakes and wetlands (Chapman, et al. 2003; St. Amour, et al. 2005; Figures 27 and 28).

Time series of δD values, δ^{18}O values, chloride concentrations, nitrate concentrations and sulfate concentrations shows that the hydrochemistry of High Creek Fen, like the groundwater hydrology, is spatially and temporally variable. Previous research has concluded that spatial differences in groundwater and surface water chemistry are primarily due to differences in bedrock and soil chemistry (Cooper 1996; Appel 1995; Bruederle 1997). However, these previous research studies either did not measure physical groundwater parameters such as hydraulic head or did not sample groundwater and surface water across seasonal gradients. Based on hydrochemical and hydrologic data collected across seasonal and spatial gradients, it is evident that spatial differences in groundwater and surface water chemistry may be driven by hydrologic dynamics.

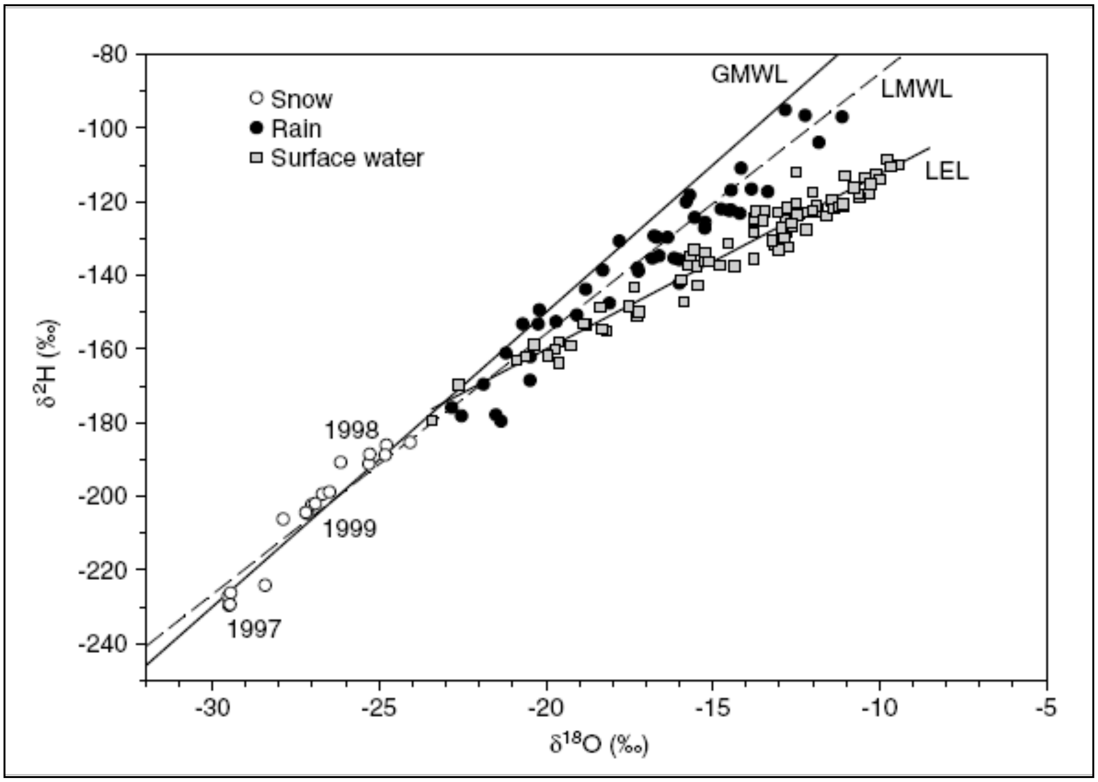


Figure 27. From St Amour, et al. 2005. Plot of $\delta^{18}O$ versus δD from surface water, snow and precipitation samples collected from lakes and wetlands in the Fort Simpson Area of the Canadian Northwest Territories. Snow samples are depleted in $\delta^{18}O$ and δD compared to rain and surface water samples.

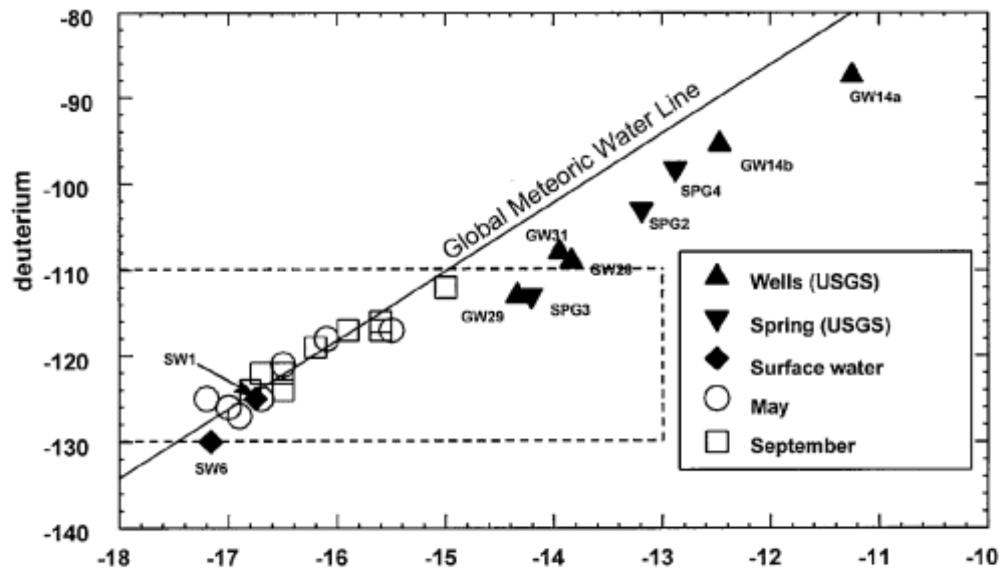


Figure 28. From Chapman, et al. 2005. Plot of $\delta^{18}O$ versus δD from surface water and shallow groundwater collected from Tarryall Creek Mire and Link Ditch Fen in South Park, Colorado. Shallow groundwater and spring water are depleted in δD compared to the GMWL.

5. Conclusion

The hydrochemistry of High Creek Fen appears to be driven by seasonally dynamic hydrologic processes. During snowmelt, the hydrochemistry is driven by pulses of meltwater inputs to shallow groundwater sources. After snowmelt, it is probable that evaporative processes exert control groundwater and surface water hydrochemistry. In addition, the chemical composition of the two groundwater sources, identified in Chapter 2, may influence the spatial variability in hydrochemistry at High Creek Fen.

The hydrochemical data presented in this chapter have added to our understanding of spatial and temporal variability of hydrology and hydrochemistry at High Creek Fen. In addition, the data have generated more hypotheses regarding the relationship between hydrologic and hydrochemical dynamics within the complex High Creek Fen ecosystem. The next step in testing some of the hypotheses generated from this research would be to collect hydrologic and hydrochemical measurements at a higher temporal resolution. Future investigations could more precisely identify the groundwater source to High Creek Fen if they sampled groundwater within a larger geographic area in the High Creek Fen watershed.

CHAPTER 4: Conclusions

The research presented in this thesis improves our understanding High Creek Fen hydrology. Instead of three groundwater sources feeding the hydrology of High Creek Fen (Cooper 1996), it appears that High Creek Fen is fed primarily by one shallow groundwater source that originates in the northwest of High Creek Fen and a secondary source may feed the eastern area of the fen. Also, the shallow groundwater flow within the fen is from the northwest to the southeast. These findings indicate the hydrology of High Creek Fen could be compromised by groundwater withdrawals in the shallow aquifer northwest of High Creek Fen. However, future research should be conducted in order to more conclusively identify the groundwater source(s) to High Creek Fen. Future research should measure physical hydrologic parameters, such as groundwater elevation, hydraulic head and stream discharge, and analyze the hydrochemical composition of groundwater and surface water throughout the High Creek Fen watershed. In addition, these parameters should be measured at more regular intervals across seasonal gradients in order to capture seasonal changes in groundwater sources to High Creek Fen.

It is evident that High Creek Fen is seasonally dynamic. The primary controls of the hydrology of High Creek Fen change depending on the season. For example, meltwater inputs to shallow groundwater sources feed the fen in the early spring, whereas evaporative processes control groundwater and surface water hydrology and hydrochemistry during the summer and fall. High Creek Fen could be very sensitive to climatic changes, especially if there is a decrease in winter snowfall in the South Park basin. Groundwater table declines could dramatically change the ecology and biogeochemistry of High Creek Fen. Future research should evaluate how climate change scenarios could affect the hydrology of High Creek Fen.

BIBLIOGRAPHY

Appel, J. 1995. *Hydrogeologic Framework of the High Creek Calcareous Fen, South Park County, Colorado*. M.S. Thesis, University of New Mexico.

Bedford, B.L. and K.S Godwin. 2003. Fens of the United States: Distribution, Characteristics, and Scientific Connection versus Legal Isolation, *Wetlands* **23**(3): 608-629.

Bolstad, P. 2005. GIS Fundamentals: A First Text on Geographic Information Systems (Second Edition). Eider Press, White Bear Lake; 543 pp.

Brand, C. and A. T. Carpenter. 1999. *Hydrogeologic and Vegetation Monitoring Plan for the High Creek Fen Preserve in Park County, CO*. Research Report, The Nature Conservancy, 106 pp.

Bruederle, L. 1997. *Nutrient, Mineral, and Vegetation Gradients in a Subalpine Fen: A Baseline Study for Long-term Impacts of Nitrogen Influx*. Research Report, University of Colorado at Denver, 39 pp.

Bullock, A. and M. Acreman. 2003. The Role of Wetlands in the Hydrologic Cycle, *Hydrology and Earth System Sciences* **7**(3): 358-389.

Chapman, J.B., Lewis, B. and G. Litus. 2003. Chemical and Isotopic Evaluation of Water Sources to the Fens of South Park, Colorado, *Environmental Geology* **43**: 533-545.

Chimner, R.A and D.J. Cooper. 2003. Carbon Dynamics of Pristine and Hydrologically Modified Fens in Southern Rocky Mountains, *Canadian Journal of Botany* **81**: 477-491.

Chimner, R.A., Cooper, D.J., and W.J. Parton. 2002. Modeling Carbon Accumulation in Rocky Mountain Fens, *Wetlands* **22**(1): 100-110.

Cooper, D.J. 1996. Water and Soil Chemistry, Floristics, and Phytosociology of the Extreme Rich High Creek Fen, in South Park, Colorado, U.S.A, *Canada Journal of Botany* **74**: 1801-1811.

Cooper, D.J. and J.S. Sanderson. 1997. A Montane *Kobresia myosuroides* Fen Community Type in the Southern Rocky Mountains of Colorado, U.S.A., *Arctic and Alpine Research* **29**(3): 300-303.

Craig, H. 1961. Isotope Variations in Meteoric Waters, *Science* **133**: 1702-1703.

Dingman, S.L. 2002. *Physical Hydrology (Second Edition)*. Prentice Hall, Inc., Upper Saddle River, 600 pp.

Gibbs, J.P. 2000. Wetland Loss and Biodiversity Conservation, *Conservation Biology* **14**(1):314-317.

Hogan, J.M., van der Kamp, G., Barbour, S.L. and R. Schmidt. 2006. Field Methods for Measuring Hydraulic Properties of Peat Deposits, *Hydrological Processes* **20**: 3635-3649.

Johnson, J.B. 1996. *Environmental Function, Vegetation, and the Effects of Peat Mining on a Calcareous Fen in Park County, Colorado.* Unpublished document for U.S. EPA Region VIII.

Johnson, J.B. and D.A. Steingraeber. 2003. The Vegetation and Ecological Gradients of Calcareous Mires in South Park Valley, Colorado, *Canadian Journal of Botany* **81**: 201-219.

Mazor, E. 1991. *Chemical and Isotopic Groundwater Hydrology*. Halsted Press, New York; 413 pp.

Mitsch, W. and J. Gosselink. 1993. Wetlands, 2nd Edition. John Wiley & Sons, New York; 539 pp.

Schlesinger, WH. 1997. Biogeochemistry: An Analysis of Global Change. Academic Press, San Diego; 588 pp.

Schwartz, F.W. and H. Zhang. 2003. *Fundamentals of Groundwater*. John Wiley & Sons, Inc., Hoboken; 582 pp.

St. Amour, N.A., Gibson, J.J., Edwards, T.W.D, Prowse, T.D., Pietroniro, A. 2005. Isotopic time-series partitioning of streamflow components, *Hydrological Processes* **19**: 3357-3381.

Smith, L.C., MacDonald, G.M., Velichko, A.A., Beilman, D.W., Borisova, O.K., Frey, K.E., Kremenetski, K.V. and Y. Sheng. 2004. Siberian Peatlands a Net Carbon Sink and Global Methane Source Since the Early Holocene, *Science* **303**: 353-356.

U.S. Environmental Protection Agency. 2001. *Threats to Wetlands*, EPA Document No. 843-F-01-002d. Accessed at http://www.epa.gov/nscep/ on March 23, 2008.